



PORTLAND CEMENT

BY

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FORMERLY

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A PRACTICAL TREATISE ON MODERN METHODS OF
MANUFACTURING AND TESTING PORTLAND CEMENT
AND ON THE CHEMISTRY OF PORTLAND CEMENT,
WITH SOME NOTES ON THE DEVELOPMENT OF CEMENT
FROM THE EARLIEST TIMES



PUBLISHED BY
CONCRETE PUBLICATIONS LIMITED
14 DARTMOUTH STREET, LONDON, S.W.1

FIRST EDITION 1934
SECOND (REVISED) EDITION . 1943

A LIST OF BOOKS ON CONCRETE
AND CEMENT IS GIVEN ON PAGE 358

FOREWORD

THE word "cement" is applied to many different adhesives and binding agents, but is used throughout this book to mean calcareous compounds employed in construction, i.e. "Portland cement." The various cements which are of more or less importance to the engineer are normal Portland cement, rapid-hardening Portland cement, water-repellent Portland cement, white Portland cement, coloured Portland cements, high-alumina cement, slag or iron cement, and cements with added admixtures to give certain qualities.

Portland cement is by far the most important cement for constructional purposes, and it is the purpose of this book to describe and to explain the chemistry and modern manufacturing methods in regard to it. The development of Portland cement from the stage described in Aspdin's patent specification of 1824 to the status of a great industry was the work of many minds, which, operating mostly empirically, arrived at a procedure which ensured a commercially useful product. From Aspdin's day the British cement industry has never flagged, and England has taken the lead in the important developments in cement manufacture. These improvements have been copied throughout the world, but England can still claim to produce Portland cement of a quality unsurpassed by any other country. The history of this development was dealt with by the author in his book "A Hundred Years of Portland Cement." At the present time much valuable knowledge exists and, except in a few minor points such as the adjustment of the setting time (which can, however, be controlled), the manufacture is performed with precision and the product is of uniform and excellent quality, in spite of the fact that the chemistry of the formation of Portland cement from its raw materials and of the changes which it undergoes on setting is still incomplete.

During the last decade important developments have taken place in the character of Portland cements. But the period of transition is not yet over. The last few years in particular have seen a considerable advance in that fundamental property of cements, the rate of development of strength, accompanied by corresponding improvement in some (but not all) other properties which are of considerable importance. Among the different, and sometimes conflicting, qualities called for in a cement are workability, economy (ability to carry cheap diluents), rapidity of hardening, freedom from moisture and temperature movement, impermeability, and resistance to attack. While the strength and rate of hardening have been increased by the manufacturer, the volume changes occurring in set Portland cement concrete remain to some extent in the control of the user. More rapid hardening may be accompanied by an increase in the evolution of heat, which is generally advantageous in cold weather but which in big masses of concrete may lead to internal temperatures liable to cause shrinkage movements on cooling unless maturing conditions are controlled with knowledge and care. In the latter case cements with a low evolution of heat are finding favour.

It is hoped that this volume will be useful to those interested in the manufacture of Portland cement ; it is the result of a study of the subject throughout the whole of the developments of the past forty years, and so far as the author is aware it contains a great deal of information not available elsewhere. The author is indebted to the British Standards Institution for permission to include abstracts of the latest British Standard Specification for Portland cement.

A. C. DAVIS.

STONE CASTLE,
GREENHITHE, KENT,
July, 1943.

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CHAPTER I

DEVELOPMENT OF PORTLAND CEMENT MANUFACTURE

PORTLAND cement is an active combination of silicates, aluminates, and ferro-aluminates of lime, obtained by the preliminary grinding and mixing of the requisite quantities of lime (usually in the form of carbonate), silica, iron oxide, and alumina, burning the mixture to incipient vitrification, and grinding the resulting clinker to a fine powder with a small percentage of gypsum to adjust the setting time. With the raw materials usually employed in Portland cement manufacture small quantities of magnesia and alkalis are present as impurities.

The name of "Portland" cement, if not the material, is handed down to us from "Joseph Aspdin of Leeds, in the County of York, Bricklayer," the inventor of a cement that was first described as "Portland" cement in 1824. It is popularly supposed that Aspdin chose this name from the similarity of the set cement to the colour of Portland stone or as a substitute therefor, but this name was not original even then. The name "Portland" for an hydraulic cement was doubtless adopted to distinguish the then new cement from similar cements used at the time, and it is on record that Smeaton (in 1756) stated that the cementing material he then made for the construction of the first Eddystone Lighthouse "would equal the best merchantable Portland stone in solidity and durability." Following Smeaton's discovery a patent was taken out in 1822 by Frost for what he called "British cement." It is most probable that in applying, in 1824, for a patent relating to "An improvement in the modes of producing artificial stone and which I call 'Portland cement'," Aspdin was simply adopting a new and suitable name for what he considered to be a building material which would be used as a substitute for Portland stone.

The history of cements is a long one—that of "Portland" cement is comparatively modern, for the past 120 years have seen its invention and its present state of perfection.

Ancient Cementing Materials

The use of a cementing material to bind together the bricks, stones, or other materials employed in construction, and also for the purpose of giving them a smooth surface adapted to receive decoration, is an art of very great antiquity. It was subsequent to the discovery of the art of brickmaking that the ancients arrived at that of burning lime. Indeed, the use of moistened clay, which was found to have a certain ductility and also to harden in drying, is certain to have preceded that of lime as a cement, for the qualities and the mode of obtaining the latter were of a nature to require some degree of scientific knowledge and experience.

The Assyrians and Babylonians appear to have employed either moistened clay or the bitumen so plentifully supplied by the springs in their countries. Some doubt, however, exists as to whether they ever really used a mortar. Antiquarians sometimes talk of coming across bricks which were cemented together with a coarse layer of lime. In other cases it is said that between the brickwork of ancient buildings, and at irregular distances, a layer of white substance is perceptible, varying from $\frac{1}{4}$ in. to 1 in. in thickness, not unlike burnt gypsum or sulphate of lime. From the peculiarly mollified state of the bricks it is probable that this white powder is nothing

more than common earth, which has undergone this change by the influence of the air on the clay composing the bricks.

The Egyptians, however, certainly used lime mortar in the construction of the Pyramids ; analyses of the mortar employed in the construction of the Pyramid of Cheops show that the ancients possessed much practical knowledge of the subject.

The Greeks at a very early period of their civilisation used compositions, of which lime was the base, to cover walls constructed of unburnt bricks. According to Plinius and Vitruvius the palace of Croesus, the Mausoleum, and the palace of Attalus were protected, or ornamented, in this manner. According to Strabo the walls of Tyre were built of stone set with gypsum, apparently a very common material in Asia Minor, the centre of the old Assyrian civilisation.

In Italy the first people to employ mortar in their buildings were the Etruscans. Gori, in his *Museum Etruscum*, mentions that in the tombs found near their ancient cities, such as Iguvium, Clusium, and Volterra, the structures were made with a cementitious mortar. Near Volterra, in 1739, a cistern entirely built and lined with that material was discovered. A branch of this nation, known as Tyrrhenians, was considered by the Greeks to have invented, or at least considerably improved, the art of masonry. Homer, Hesiod, Herodotus, and Thucydides speak of them under that name, and call their walls by the word "tyrsis," instead of "teichos," the name used by more modern authors. The word "tyrsis" is supposed to have had the same signification in the Etruscan language, and the towers erected for the purpose of fortification were called "tyreis" by the Greeks.

The Romans derived their knowledge of the arts from the Etruscans and the Greeks. They added little to the general stock of knowledge regarding the use of limes, but Vitruvius is the first author upon the subject whose work has descended to us ; he shows that the ancients, although they adopted a different scientific phraseology, knew as much of the laws regulating this branch of chemistry as was known in the eighteenth century. For all practical purposes Vitruvius was as safe a guide as most of the authors who treated the subject subsequently, until we arrive at the researches in France of M. Vicat. Plinius and St. Augustine occasionally refer to limes and cements ; the former principally to complain of the malpractices of the builders, the latter to seek metaphysical comparisons.

On the revival of literature after the Middle Ages the authors who treated upon the art of building, such as Albertu, Palladio, Bullet, and Plondel, did little more than follow in the tracks of Vitruvius. There was a difference of opinion, it is true, as to the quality of sand which it was most advisable to use ; some new limes, some pozzolanas, trasses, and ashes were employed to give to certain limes the faculty of setting under water, but until about the middle of the nineteenth century no advance seems to have been made towards ascertaining the principles which regulate this branch of chemistry.

It is worthy of remark that the more useful arts do not appear to be carefully studied until the practical results they are capable of producing are ascertained ; then the rules drawn from such results are received implicitly for a long period, and any attempt to ascertain the laws which regulate them is regarded as useless. The human race appears to attain empirical knowledge quickly ; scientific knowledge arrives at a much later period.

Smeaton's Experiments

The first serious attempt to ascertain the causes which gave some limes the power of setting under water, and which modified their rates of hardening, was

made by the father of civil engineering in England, namely John Smeaton, in 1756. Being at that time engaged in the construction of the first Eddystone lighthouse, he found it necessary to have a cement capable of hardening at once in water. He therefore began a series of experiments which has been detailed in his account of that great work. The results he arrived at were remarkable, not only for their practical utility but also as an illustration of the ease with which a very acute observer may stop short of the attainment of a great truth. Smeaton found that the commonly-accepted opinion in his time, namely, that the hardest lias limestones of Aberthaw gave the best limes, was only true so far as regarded each quality considered by itself. That is to say, that of limes not fit to be used as "water cements" those made of the hardest stones were the best for certain uses in the air; but that whether obtained from the hardest marble or the softest chalk such limes were equally useless when employed under water. He found, indeed, that all the limes which could set under water were obtained from the calcination of such limestones as contained a large portion of clay in their composition. His experiments led him to use for the important work of the lighthouse a cement compounded of blue lias lime from Aberthaw and of pozzolana brought from Civita Vecchia, near Rome. Even at much later periods it was difficult to employ a better material than this, except that the price would ensure a preference to the Roman cement ultimately made but then unknown.

Smeaton in his records gives a table showing that all the "water limes" were obtained from limestones containing clay in chemical combination in proportions varying from three-fourteenths to one-seventeenth, and goes on to say: "It remains a curious question, which I must leave to the learned naturalist and chemist, why an intermediate mixture of clay in the composition of limestone of any kind, either hard or soft, should render it capable of setting in water in a manner no pure lime I have yet seen, from any kind of stone whatsoever, has been capable of doing. It is easy to add clay in any proportion to a pure lime, but it produces no such effect; it is easy to add brick dust, either finely or coarsely powdered, to such lime in any proportion also; but this seems unattended with any other effect than what arises from other bodies becoming porous and spongy, and therefore absorbent of water as already hinted, and excepting what may reasonably be attributed to the iron particles that red brick-dust may contain. In short, I have as yet found no treatment of pure calcareous lime that rendered it more fit to set in water than it is by nature, except what is to be derived from the admixture of trass, pozzolana, and some ferruginous substance of a similar nature. . . . With regard to the samples of material that were constantly kept under water, they did not seem inclined to undergo any change in form, only to acquire hardness gradually, in so much that I did not doubt but to make a cement that would equal the best merchantable Portland stone in solidity and durability."

Research in France

The stress Smeaton laid upon the presence of the ferruginous substance led many chemists to attribute the hydraulicity of limes to the presence of oxide of iron. Investigators such as Guyton de Morveau and Bergmann, finding oxide of manganese in the hydraulic limes they analysed, regarded it as producing the effect in question. Their researches were nearly contemporaneous with those of Smeaton. Some thirty years afterwards De Saussure observed that the lime of Chamonix set under water, though entirely without manganese, and he, like Smeaton, attributed

this faculty to the presence of clay. In 1813 Colets Descotils, on analysing the compact marl of Senonches, which yields on calcination a lime capable of setting rapidly under water, found it contained nearly one-quarter of silex, which led him to the conclusion that the cause of the phenomenon consisted in the presence of a large quantity of siliceous matter, disseminated in very fine particles in the tissue of the stone itself. Later, to continue with a quotation from Vicat: "The opinion of Descotils did not weaken or invalidate that of De Saussure, since clay contains generally more silex than alumina; and the two chemists agreed, moreover, in considering the oxide of manganese, if not as a useless element, at least as one which was not essential."

With the intention of putting an end to all doubt upon the subject Vicat decided to proceed synthetically, and to compose hydraulic limes entirely by burning different mixtures of common lime, slaked spontaneously with clay. The successful result of this experiment surpassed his most optimistic hopes. All the clays rich and soft to the touch gave the same result. Vicat's experiments were repeated in Paris in 1817 with the limes of Cleys and of Champigny and the clay from Vauvres. Further experiments, by St. Leger in England and by Raucourt de Charleville in Russia, at that time also confirmed the results obtained by Vicat. The subsequent researches have confirmed the theoretical opinion which guided Vicat in his experiments, with a few recent important rectifications of detail. John of Berlin, Fuchs of Munich, Pasley, Ansted, and Way in our own country, and many experimenters in France as well as most of the scientific authors who have treated upon the subject throughout the world, have arrived at nearly the same conclusions as Vicat with respect to the causes which influence the different actions of lime.

Even with the data available it is difficult to say, however, when and where the first more modern mortars were used. The term or name "mortar" is of Roman derivation, owing to the Romans using a *mortarium* to secure homogeneity of the binding material. The name should therefore be regarded in a generic sense, and applicable to all preparations used in binding together in structural form stones, bricks, and other building materials.

Roman Cement

A substantial advancement in cements occurred near the end of the eighteenth century, when Medina cement and Roman cement were introduced. Patents for the latter material, which was more generally employed, described it as applicable to the manufacture of a "Certain Cement or Terras (trass) to be used in Aquatic and other Buildings and Stucco Work."

Roman cement consisted of "reducing to powder certain burnt stones or argillaceous productions called 'noddles' of clay, and using that powder with water so as to form a mortar or cement stronger and harder than any mortar or cement now prepared by artificial means." The nodules of clay were described as "certain stones of clay or concretions of clay containing veins of calcareous matter having frequently but not always water in the centre, the cavity of which is covered with small crystals of the above calcareous matter and the noddles agreeing very nearly in colour with the colour of the bed of clay in or near which they are found." With "two measures of water and five measures of the powder thus described," Parker, the inventor of Roman cement in 1796, says his cement is then made "and will set or become indurated either in ten or twenty minutes after the operation has ceased either in or out of water." He observes, in conclusion,

"the less water is used the better, and the sooner the mortar or cement is used after being made the stronger and the more durable it will be."

Contrary to the practice hitherto obtaining—and adopted by Smeaton—of only burning the raw materials sufficiently to drive off the carbonic acid gas and then reducing to powder by slaking with water, the "noddles of clay" for the manufacture of Roman cement were burnt with "a heat nearly sufficient to vitrify them," and the burnt material was then reduced to a powder by any mechanical or other operation.

"Water Cement"

It was several decades before experimenters in making a new cement to supersede Roman cement arrived at the point that mixtures of lime and clay or chalk and clay in certain proportions, if only calcined in a kiln, produced what we should now term hydraulic lime—but which the originators termed "water cement"—and yet by increasing the heat in the kiln so as to produce in the raw materials a state of incipient vitrification a Portland cement as we know it to-day could readily have been produced. Suffice it to say that, starting with the notion of imitating Roman cement, early inventors arrived at the idea that when chalk and clay were mixed and burned an hydraulic material was produced. It is on record that in the beginning of the industry all hard clinker produced by incipient vitrification was rejected—to-day this is the only material used for grinding into cement.

Early Nineteenth-Century Manufacture

The invention of a ground hydraulic lime was received with acclamation as a new and valuable cement for construction purposes to supersede the Roman cement used at the beginning of the nineteenth century, and there must have been a variety of qualities of this lime on the market owing to the uncertainty as to its actual constituents and manufacture. For instance, the renowned London civil engineer, Sir I. K. Brunel, changed over from the Roman cement he had previously used on important civil engineering works to the new "Portland cement" invented by Aspdin in 1824; and paid heavily in price for the new product with which to finish the construction of one of the first tunnels under the Thames in 1838.

Although Frost, in 1822, patented and produced what seemed to be a ground hydraulic lime (because he merely calcined his mixed raw materials), and which he termed "British cement," yet Aspdin followed two years later with a similar material, made in a less exact way according to his patent, and again only calcined his raw material mixture, which he called "Portland cement," and this was the material Brunel preferred. Hence to-day's name for what is apparently a different product from that which had been marketed in earlier times. Whether or not during the experience of those two originators the burning of raw materials similar to those used by Frost and Aspdin was secretly changed, or increased from mere calcining to a heat involving incipient vitrification, which is essential for the manufacture of Portland cement as we know it to-day, history does not relate. So we can only arrive at the fact that Aspdin certainly was the inventor of the name "Portland cement" if nothing else. It may well be supposed that Aspdin actually carried out the manufacture of Portland cement secretly and without disclosing its precise manufacture in his patent; but this is conjecture, and both Frost and Aspdin may only have manufactured the material as their patents show it to be, namely, an improved and ground hydraulic lime.

Previous to and during this period, in the early part of the nineteenth century,

a number of works for the manufacture of different cementing materials sprang up, and there were made a Roman cement by Parker at Northfleet in Kent for general building purposes, a "British cement" by Frost at Swanscombe in Kent, a "Portland cement" (as he termed it) by Aspdin at Wakefield, and the same product by Aspdin's son at Gateshead; while similar and other cements were made by the firm of Francis and White at Nine Elms, London. The firm of Francis and White dissolved in 1827, and in that year John Bazley White took over Frost's works at Swanscombe for the manufacture of Frost's and Roman cement.

On the date of the commencement of the manufacture of the material called Portland cement as we understand it to-day, there is less definite evidence. Indeed, from a search of the Patent Office files it can be said that there is no specific inventor recorded of the manufacture of to-day's Portland cement, or in principle any cement closely or actually resembling the constitution of Portland cement; and while it is true that the name "Portland" cement is recorded by Aspdin for a cement possibly differing in character from that previously used in his time (and differing also from the Portland cement of to-day), yet we can only suspect that the actual initial introduction of to-day's Portland cement was evolved rather than invented at a date much later than Aspdin's patent. The material introduced by Aspdin as Portland cement and the materials which developed from its introduction evidently continued to be sold under the generic name and, whether as a result of experiment or accident afterwards, one cannot go further than state that it was approximately from the materials, but not by the identical process, used by Frost to make his "British cement" in 1822 and by Aspdin for his "Portland cement" of 1824, that Portland cement was evolved.

Since these inventions followed closely on the manufacture and marketing of Roman cement it is evident that in the invention of this new cement the danger of overburning in the manufacture of Roman cement was present to the minds of Frost and Aspdin, for any of the overburnt septaria was useless. The required heat was just enough to reduce the weight of the raw materials to a minimum, and if the temperature of the kiln exceeded what was necessary to produce that result, then the Roman cement product was unmarketable. It is from White's factory at Swanscombe that the first evidence comes that the hitherto only calcined raw materials came to be "burned with unusually strong heat until the mass was nearly vitrified," and the claimant of this process was I. C. Johnson, then manager of White & Sons. We have the definite claim of Johnson to guide us approximately on this point, and as he joined the firm of White & Sons in 1827 in his sixteenth year it was some years after (possibly 1845) that he produced Portland cement, as we to-day understand the material, in contradistinction to the invention once termed by Aspdin "Portland" cement.

So the evidence shows that the new cementing material—similar to ground hydraulic lime as we know it—was invented first by Smeaton, then by Frost in 1822 and called by him "British cement," followed by Aspdin in 1824 with his specification for "Portland cement"; yet all were a more or less similarly prepared material—both Frost and Aspdin having the published evidence before them of Smeaton's discovery in 1756 of a "cement that would equal the best merchantable Portland stone in solidity and durability." Finally we have the claims (but not the patent) of I. C. Johnson, who at Frost's old factory at Swanscombe some time after the year 1840 produced for J. B. White & Sons the early Portland cement. The Swanscombe Works to-day is one of the largest Portland cement factories in Europe, with a capacity of 500,000 tons per annum.

White's Portland cement soon began to be demanded all over the world and at home, with the result that many new factories for the manufacture of cement sprang up. The Port of London assisted in the establishment of a belief that Portland cement was indigenous to its neighbourhood and could only be produced by a combination of the chalks and clays found on the banks and shores of the rivers Thames and Medway. In France and Germany, however, large works came into existence not long after, and it may be said that London, Boulogne, and Stettin were the chief centres of this industry in the three countries in the first quarter of a century of its history.

Second Half of the Nineteenth Century

In 1850 there were in England probably four small Portland cement factories, situated at Swanscombe, Northfleet, Wakefield, and Gateshead. Development was first hindered by irregularity both in quality and output, and by the competition of the so-called Roman cement. It was only during the second decade after its introduction that improvements in the manufacture of Portland cement, brought about by an increasing knowledge of the chemistry of the subject, were beginning to bring the material more into favour with engineers to the gradual displacement of Roman cement, although the latter, being particularly suitable for some purposes, continued to be manufactured to a certain extent right into the beginning of the twentieth century.

In France, Portland cement first began to be used about 1850. A factory at Boulogne-sur-Mer, originally engaged in the manufacture of other cements, was then used exclusively by the proprietor (M. Dupont) for the preparation of Portland cement, the regularity and excellence of the supplies being good propaganda for the material. In 1850 MM. Dupont and Demarle began to deliver fairly large quantities of Portland cement; their first experiments date from 1846, but regular manufacture was only effected about 1848-50. Demarle found means of utilising the marly chalk beds discovered by Vicat, which to this day maintain the factory at Boulogne-sur-Mer. He was able, within a relatively short space of time, to improve manufacture as regards the treatment of raw material, and particularly the proportions to be used, and so bring it to such perfection that his methods were followed.

Further experience and improvements in machinery and appliances, and a gradual realisation that the manufacture of cement is essentially a chemical process, were bringing about an increasingly rapid growth of the industry. At the Great Exhibition in Hyde Park in 1851 tests were made with "briquettes" of cement, and the breaking strain of neat Portland cement was 414 lb. per square inch at three months. There is still preserved at White's factory at Swanscombe a large block of concrete, made with their Portland cement, which was exhibited at this Exhibition. The Exhibition undoubtedly gave a great impetus to the industry, and it is interesting to note that in 1859 John Grant, Engineer to the Metropolitan Board of Works, decided to use Portland cement in the construction of the London Drainage Canal, and published his reasons in the *Proceedings* of the Institution of Civil Engineers. This decision no doubt also helped to bring the new cement to the front.

Other factories sprang up, and the presence of ample supplies of chalk and the excellent alluvial clay of the Medway (materials which were found to be unsurpassed for the manufacture of Portland cement) offered strong inducements to manufacturers, and the Thames and Medway districts became the "cradle of the industry." The first works on the Medway was established at Frindsbury, near Rochester,

followed by others at Upnor, Halling, etc. The number of factories on the Thames also became rapidly augmented, and met with more or less success.

The progress of science was extremely slow and differed vastly from the pace of modern times, since it took nearly thirty years—from 1824 to 1852—to improve upon the manufacture known to Asplin up to the standard of quality manufactured by G. F. White, who stated in his paper before the Institution of Civil Engineers in 1852 that “in seven days Portland cement attains a cohesive power of more than 100 lb. per square inch.” Therefore the Portland cement of 1852 was even inferior to modern hydraulic limes; and the fact that modern Portland cement has a strength of 1,000 lb. per square inch at seven days gives some idea of the degree of burning of cement at that date. Such cement was even then, however, called “most highly calcined,” and to this cause must be referred the success of the artificially-produced Portland cement known at that time. G. F. White’s paper is an enlightening record of the early days of the use of Portland cement in preference to Roman cement, and is quoted at length in the author’s book “A Hundred Years of Portland Cement.”

The adoption of these artificially-compounded materials in preference to those made from natural cement stones had for some time been gaining ground. The chief application was in connection with bricks, which could be adjusted in position before the cement began to set, even though used neat. The properties, however, which rendered cement valuable as a jointing medium in brickwork operated unfavourably to its use in masonry, since waste from rapid setting would ensue, and to avoid such waste it was very common to re-work the cement, thereby interfering with the setting process. Prejudice in France against quick-setting cements made from natural stones had led to the extensive use of hydraulic limes, with an admixture only of sand, pozzolana, trass, or artificial pozzolanas made of calcined clays. Though successful in some cases, in the majority of instances where artificial pozzolanas had been used on a large scale failure had followed. Vicat examined the causes of these failures and concluded that the hydrochloride of magnesia in sea-water penetrated the imperfectly carbonated portion of the cement and led to disintegration. He was thus led to believe that pozzolanas produced by volcanic heat differed from those produced artificially, and the inference would be that to create a perfect cement it was necessary to mix the clay with the carbonate before calcination.

Contemporaneous with these researches in France were those of Frost in this country, but, as he did not apply to his mixture the needful calcination, Frost’s cement did not attain the strength of Roman cement, nor did it dislodge that material from public esteem. General Pasley appeared to have shared the opinion of Frost that artificial cements would supersede natural cements, and made many experiments on the proportions in which carbonates and clays should be blended. The problem was that of producing, by combination of carbonate of lime and alumina, a cement superior to those resulting from the calcination of natural stones. This had apparently been attained in Portland cement, a material combining the characteristics of the best cements with the properties of limes. This two-fold property was almost peculiar to Portland cement and not shared by those made from natural stones. Ordinary Roman cement was rarely mixed with a larger quantity than two volumes of sand to one of cement; it was not used for concrete, and when employed as grout its setting properties were so much injured as to leave it questionable whether it added to the solidity of the construction. On the other hand, four, five, or six parts of sand might be mixed with Portland cement to form mortar, the proportion

being a question of the time afforded for setting and not of deterioration of quality from excess of foreign matter.

According to White, in making Portland cement in 1852 chalk and clay mixed in definite proportions were carefully ground together in water, and the mixture then run off into backs or reservoirs. After attaining a specific consistency it was artificially dried and removed to the kiln for calcination to a much greater extent than that needed for lime and Roman cement. It was next delivered to the mill for grinding, and after being sifted it was packed for use, the important points of uniformity in colour and time of setting having been ascertained by experiments. Daily tests of the strength of the cement were made by moulding it into bricks, which twenty-four hours after setting were exposed to rupture by extension. The increase in strength was then considered remarkable. In seven days it attained more than 100 lb. per square inch, and at the end of three months a strength equivalent to 414 lb. per square inch. To the variety of processes, to the extra fuel employed, and to the time and care expended upon the manufacture, the higher cost of Portland cement was attributed by White.

Vicat had made some observations on what he called *ciments grules*, in which he mentioned Portland cement. He said setting was variable from an hour to weeks, and the difficulty of grinding and the quantity of fuel required were in his judgment insuperable obstacles to its adoption, but he stated that if its property of progressive hardening and cohesive powers be examined they would be found quite remarkable and greatly in excess of the best natural hydraulic limes—200 lb. per square inch being the greatest resistance to compression obtainable by limes, while the highly-calcined cements acquired that hardness in a few days and reached 700 lb. per square inch, a resistance superior to that of calcareous lithographic limestones. Two volumes of sand reduced this resistance to about 350 lb. per square inch; but these cements solved the problem of producing an artificial stone equal in hardness and density to compact limestones.

G. F. White mentioned that the eventual resistance to compression of Portland cement then was: When used neat, 2,000 lb. per square inch; with two volumes of sand, 1,250 lb.; and as a concrete stone, about 1,750 lb. (To-day the compression strength of concrete made with 4 parts of ballast, 2 parts of sand, and 1 part of rapid-hardening Portland cement reaches 6,000 lb. per square inch when three days old.) According to Vicat the most noticeable feature of these cements was their great hardness and the resistance they consequently offered to the combined action of the sea and shingle in the most exposed situations, agencies which very speedily destroyed the pozzolanic mixtures and the best hydraulic limes.

At that time the agency to which cements owe their power of setting and consequent induration was not well understood. It was commonly considered that this was due to absorption of carbonic acid gas from the atmosphere, but G. F. White stated that about that time it was ascertained by chemists that it was the chemical union of the lime with silica and clay, and the consequent formation of a double silicate of lime and alumina, that produced the effect. The peculiar affinity of the lime to the alumina and silica appeared to be exerted most powerfully with those cements, whether natural or artificial, which were most highly calcined and consequently set the slowest, and to this cause he referred the excellence of the artificially-produced Portland cement. The large proportion of sand and gravel that could be mixed with Portland cement without materially affecting its cohesive power gave it an immense advantage over lime.

It is of interest to note also that G. F. White records experiments made on the

adhesion both of Portland and Roman cements to various stones. The average of these tests showed that a force of 5,276 lb. was required to tear asunder two 6-in. blocks of Portland stone joined with Portland cement, or 146 lb. per square inch of sectional area; while with granites the resistance was but 97 lb., 76 lb., and 57 lb. per square inch respectively. The joint between the cubes of stone was barely one-eighth of an inch in thickness, and the stone was broken before the separation of the joints could be effected. The results further showed that the connecting power of Portland cement compared with Roman cement was as $3\frac{1}{2}$ to 1.

G. F. White pointed out that cements made by Pasley or Frost were not identical with the material then known as Portland cement. The constituents of the three cements were, however, similar, and they differed but little in the proportions employed; but both Pasley and Frost stopped short at the all-important point of calcination and they rejected as overburnt the material which was later known to yield the most valuable product. The aim of Pasley had been to rival the natural cement, and he had succeeded; but it had been reserved for another operator to produce in Portland cement a material which should far outstrip in cohesive power any of the natural cements known in this country.

The position of the Portland cement industry about the end of the second quarter of a century after its initiation is again well illustrated by a writer in 1874 (George R. Burnell), who referred to the "new" Portland cement then introduced on to the market. Burnell states that the experience of the best Continental engineers had led them to prefer the use of artificial hydraulic limes wherever natural ones were not to be met with. There were, he said, two methods of preparing artificial hydraulic limes. The first, the more perfect but at the same time the more expensive, consisted in mixing the slaked rich lime with a certain proportion of clay and burning this compound, the lime in this case going through a double calcination. The second method consisted in mixing, instead of the slaked lime, soft calcareous materials such as chalk with the clays, or the tufas of some of the older formations, and in reducing the whole to a paste by grinding them together in a mill. Generally speaking, 20 parts of dry clay were mixed with 80 parts of very pure rich lime, or with 140 parts of carbonate of lime; but if the lime or the carbonate contained clay in its composition a smaller proportion was necessary.

Burnell records that at Meudon, near Paris, extensive works were erected, under the direction of Vicat, by MM. Brian and St. Leger for the manufacture of artificial hydraulic limes from the chalk and clays of that country. Previously to being ground the chalk was divided into pieces of the size of the fist. A large vertical mill worked with two horses crushed and mixed the materials, with a plentiful supply of water, in the proportion of four parts of chalk to one of clay. The liquid was run into five troughs placed at successive differences of level, and deposited in them the matter it held in suspension. A double set of these troughs was necessary in order that one might be worked whilst the liquid was depositing in the other, and it was found that the shallower the troughs were in proportion to their surface the more rapidly did the deposition take place. As soon as the deposited matter became of sufficient consistency to support manipulation it was made into small prisms with a mould. The prisms were then placed on a drying platform and allowed to dry until they arrived at the state of freshly-quarried limestone. They were then put into a kiln and burnt.

In England a somewhat similar process was followed in the manufacture of Portland cement. Burnell considered this nothing but an artificial hydraulic lime composed of the alluvial clay of the valleys of rivers, mixed in definite proportions

with the chalk of the same geological districts. These materials were very finely comminuted under mills, and with water; they were allowed to deposit, and were then desiccated and burnt. But here began the different, and the most delicate, part of the manufacture. Instead of merely driving off the carbonic acid gas, calcination was taken to a point which produced vitrification in a very considerable portion of the contents of the kiln. The lime was, in fact, overburnt, and often irregularly so. Great care was therefore required in grinding the different products of the calcination to secure a proper uniformity in their times of setting; all the overburnt limes, like the natural cements, slaked with so much difficulty when in large masses as to require to be broken up before being used. There was also attached to the Portland cement the danger of occasionally expanding in setting. For this reason Burnell recommended that it should never be used unless in positions where this action, which the manufacturers did not appear to be able to control, would not be prejudicial to the work. When carefully prepared it was invaluable for external plastering, because it did not allow of the formation of vegetation like the natural cements, but unless great care had been taken in its manufacture it should not be used for large masses of masonry.

There was then a material manufactured in the Midland Counties and sold in London under the name of Portland cement which Burnell recommended should be used with even more caution than the material it was intended to represent. This was composed of ordinary blue lias lime, mixed in powder with definite proportions of clay obtained from the intercalated beds of the same geological formation, and burnt in closed retorts. With this cement solidification did not take place with sufficient rapidity to allow of its being used under water in many cases where the real Portland cement would succeed.

The use of the then Portland cement advanced so slowly, however, that so late as 1874 Lieut.-Col. Sir Wm. Denison, Royal Engineers, wrote in his "Notes on Concrete" published in that year: "The very general employment of the mixture of lime and gravel, commonly known by the name of concrete, in all foundations where, from the nature of the soil, precautions against partial settlements appear necessary, and the great probability of an extension of its use in situations where the materials of which it is composed are easily and cheaply procured, must of course render it a subject of great interest to the engineer."

As further illustrating the progress of the Portland cement industry in the United Kingdom a few years later (1878) it is of interest to quote from a further article by Burnell: "Portland cement as manufactured in the neighbourhood of London is made by a mixture of the chalk and clay of the alluvial formations of the lower parts of the Thames and Medway; the chalk being derived from the upper members of that formation, or from the chalk with flints, and the mud being principally derived from the deposition of the tidal waters. These ingredients are ground with a great quantity of water under edge rollers, and they escape through species of sieves in the requisite proportions, to flow off into large backs or reservoirs, where they part with a great proportion of the water used for their levigation. Of course there can be little certainty as to the proportions of the chalk and clay that are thus mixed, as they may both of them vary much in their chemical composition; but as a general rule the manufacturers endeavour to secure a mixture in which the carbonate of lime should be present in about the proportion of 60 per cent. of the whole mass, the silicate of alumina in the proportion of 34 per cent., and the rest would be composed of various ingredients that are found in the alluvial mud. After the mixture has been allowed to settle in the backs it is dug out in the plastic state

cement which gives a substantial margin over them to allow for the element of human error in testing. The actual increase in strength is illustrated in *Fig. 1*, showing the development in the quality of Portland cement since 1862.

Rapid-Hardening Portland Cement

The greatest advance during the past few years has been the introduction of rapid-hardening Portland cement, which was first produced in Great Britain. Rapid-hardening Portland cement is a superfine Portland cement, costing a little more than ordinary Portland cement but considerably cheaper than high-alumina cement; unlike high-alumina cement, rapid-hardening Portland cement is a true Portland cement made with the same raw materials as Portland cement but of a more refined manufacture. It was brought within the scope of a British Standard Specification for the first time in 1940. The process of manufacture is similar to that of Portland cement in that it demands the same materials, conditions, and machinery, but it differs in respect of chemical composition and degree of burning and grinding. The CaO content is increased, and this entails careful proportioning and mixing of the raw materials. This increase of lime content is liable to render the cement unsound unless the burning is effected with precision and is sustained for a longer time than in the case of ordinary Portland cement. The extra burning renders the resultant clinker harder than usual, and this demands more careful manipulation, more power, more plant, and more wear and tear in the process of grinding. Clinker has no cementitious properties until it is ground into an impalpable flour, and as the setting and hardening of cement depend entirely upon the area of the surface of the particles produced it is obvious the ideal is obtained when the residue remaining on a 170-mesh B.S. sieve is the least attainable. In the case of rapid-hardening Portland cement produced in Great Britain to-day the residue is as low as 1 to 2 per cent. on the 170-mesh sieve (having 28,900 holes to the square inch). The increased fineness of rapid-hardening Portland cement is expressed by the latest B.S.S., which permits a residue of only 5 per cent. on the 170-mesh sieve compared with a residue of 10 per cent. in the case of ordinary Portland cement.

A feature of rapid-hardening Portland cement is that it is not quick initial setting, and therefore allows ample time for mixing and placing the concrete in position before the set commences. The comparative strengths of rapid-hardening and ordinary Portland cements are shown in *Fig. 1*.

Methods of Testing

The introduction of standard specifications for cement in various countries has naturally been accompanied by standardisation of the methods for making the various tests prescribed. It is very much to be doubted, however, whether methods of testing cement can be said to have kept pace with the progress in the improvement of the quality of the article itself.

There is between the various national specifications some general agreement as to the qualities required in cement, and in respect to which it is to be submitted to test. These qualities, broadly, are the chemical composition; the time taken to set; the strength to be attained in a given time; and constancy of volume or soundness. It is common practice also to prescribe the fineness to which the cement is to be ground, but, as fineness of grinding is only a means towards attaining the other qualities desired in a cement, there is some divergence of opinion as to the need to specify it. Wide divergence comes in when it is necessary to decide how such

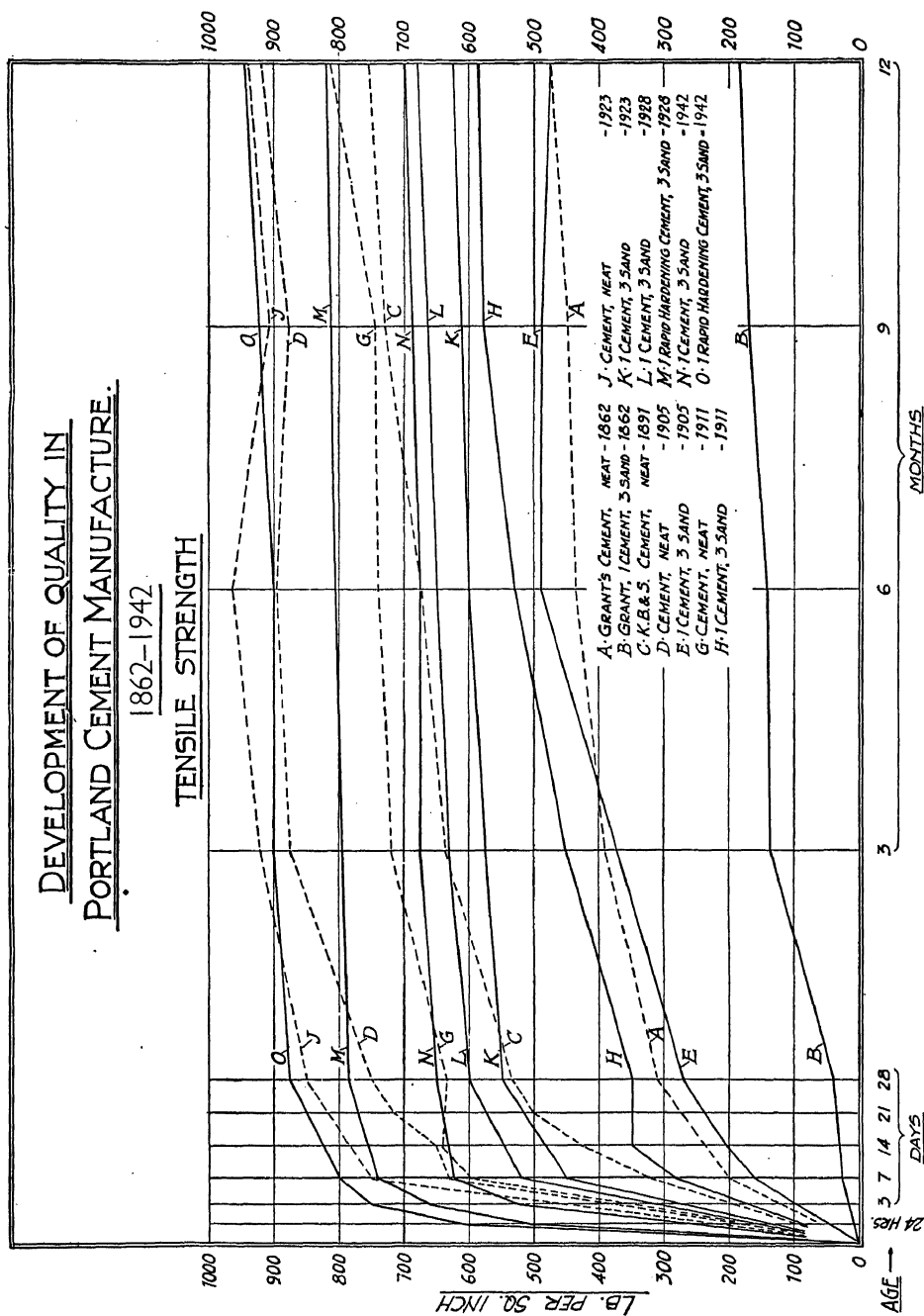


Fig. 1.

qualities shall be determined. For example, it is easy to prescribe that the cement when mixed with water shall not "set" or harden within a certain time, but it is necessary also to decide how and by what means the test shall be made. Here the difficulties inherent in standardising cement testing begin to manifest themselves. All cements are affected in their characteristics by the amount of water used with them, and by the temperature and other conditions obtaining during testing.

It is therefore necessary, as a first step, to prescribe the quantity of mixing water to be used, and short of prescribing a fixed percentage there is yet no method by which testers without consultation will exactly agree as to the proper quantity of water to be used for mixing a given sample of cement. Vicat introduced the method of applying the end of a weighted rod to the surface of cement paste and determining its consistency by the time and depth of penetration, and this procedure is used to-day in some specifications. It is, however, very approximate, and in fact can only be used with reasonable success if the cement is mixed with a quantity of water far in excess of that which it really needs; the results are also influenced by the amount of mixing the tester has given the paste. The British Standard Specification now prescribes that this method shall be used subject to the application of a factor to reduce the quantity of water.

With this initial difficulty in the way of accurate cement testing still to be satisfactorily solved, it is perhaps not surprising that the process is lacking in precision and scientific application. There is room, and indeed urgent necessity, for an improvement in the methods of testing cement which will place it on a more scientific and exact basis. To this end the 1940 edition of the B.S.S. provides that the quantity of water required to produce a paste of normal consistency shall be 0.78 of that required to give a paste which will permit of the settlement of the Vicat plunger to a point 5 mm. to 7 mm. from the bottom of the Vicat mould. This specification also provides that the proportion of water for gauging cement-sand briquettes shall be determined by the formula $\frac{1}{4}P + 2.50$ where P is the percentage of water required to produce a paste of normal consistency for the Vicat test.

The British Cement Industry

While fifty years ago the manufacture of Portland cement was empirical, at the present time it ranks among the great chemical industries of the world, carried on by trained chemists and mechanical and electrical engineers. To-day in the United Kingdom the manufacturing capacity exceeds 7,000,000 tons per annum. The consumption at home is less than this tonnage by at least half a million tons a year, as about three-quarters of a million tons are usually exported.

The centres of the manufacture of Portland cement in Great Britain are well distributed, namely, in the north and south, the Midlands, the east of England, and Wales in the west. In Ireland works are situated at Larne, Wexford, and in other places; and in Scotland, near Glasgow and Edinburgh. Altogether there are to-day about 65 factories in England, 4 in Wales, 4 in Scotland, and 4 in Ireland, owned by many different manufacturers or companies.

The normal size of a modern cement factory is one having an output of at least 2,000 tons of Portland cement per week, and throughout the British Isles there are factories producing 7,500 and 10,000 tons of cement per week each. The capital cost of all the factories in the United Kingdom, based upon a broad estimate including the usual accessories of the business, would approach £25,000,000, and the number of workers directly engaged in the industry is about 12,500.

Up to the beginning of this century most of the operations were carried out by man power, working sometimes under very uncomfortable conditions ; for example, in loading and discharging the chamber and other types of kilns used. Not only was this work heavy, but men had to work in temperatures which made the wearing of even the scantiest of clothing almost unendurable. Some progress had been made in the mechanical mixing of raw materials, and ball and tube mills had been substituted for the earlier millstones used for grinding clinker. Nevertheless, conditions were such that it was mainly only lowly-paid agricultural labour which was willing to enter the cement factories of those days.

From the early years of the present century an almost complete revolution has been effected in cement works operation, and all heavy operations are to-day more efficiently conducted by machines. The digging of the raw materials, formerly carried out by small armies of men with great personal exertion and at considerable risk, is now done by mechanical excavators. The chamber and other kilns are replaced by rotary kilns, in which the mixed raw materials and fuel are automatically and continuously fed, and the whole drying and clinking operation carried through under the control of one man. The dusty and heavy work of shovelling the ground cement into casks and sacks by hand and wheeling the packages on hand trucks to the loading platform is replaced by automatic filling and weighing machines and conveyors.

In the early days England was supplying the world with cement ; but it was soon discovered that the material could be made from a variety of geological deposits containing as their chief constituent carbonate of lime, which is widely distributed in the earth's crust. Thus, after a time, the great cement-producing centres in England found their trade abroad contested by a growing local manufacture, and the exports to many foreign markets were continued at such prices as to be barely remunerative. Shortly after its initial manufacture in England, France quickly followed in her own production of Portland cement ; Germany, too, very soon developed her own cement manufacture. At the same time our largest single customer, the United States, out-distanced us and developed her own manufacture with such rapidity and on so huge a scale that European manufacturers quickly found themselves deprived of an outlet for a great quantity of their products. The alteration in trading conditions due to the development of Portland cement manufacture in other countries led to an urgent necessity to effect economies and improvements in the quality of cement manufactured at home, and as a result the gradual improvement of quality has always made British cement superior in quality in the markets of the world.

The World's Production

In one hundred years or so since Aspdin's time the world's output of cement has reached 105,000,000 tons annually, and it is reasonable to assume that with the enormous progress to-day in the uses of Portland cement the consumption will continue to increase ; in fact, the increase in consumption is, curiously, rather automatic ; there is no competitive material, and a usual expectation is that an aggregate of 1 per cent. per annum increase will be reached. Separated into Continents the normal production of Portland cement is approximately now as follows : America, 50,000,000 tons ; Europe, 45,000,000 tons ; Asia, 7,000,000 tons ; Australia, 2,000,000 tons ; Africa, 1,000,000 tons ; total, 105,000,000 tons. It is of interest here to examine the figures of annual production of cement per head of the population in some of the chief cement-producing countries. These figures are :

United Kingdom, 3 cwt. ; Belgium, 7 cwt. ; United States, 7 cwt. ; Denmark, 4 cwt. ; Norway, 3 cwt. ; Germany, 3 cwt. Some 65 per cent. of the Belgian cement production is normally exported, but in the case of the United States by far the greater proportion is consumed within its own territories. The United States may therefore claim to have the highest consumption of cement per head of population—as is indeed to be expected in a vast country not fully developed but with a large and enterprising population.

Fundamentals of Portland Cement Manufacture

The cement manufacturer has two principal objects in view, viz. to make good cement and to make it economically. There are different means of attaining these ends, and the student of the subject may at first be inclined to think that cement manufacture is in a chaotic condition because of the various answers that different experts may give to the same question. A further study, however, reveals that the emphasis laid upon the importance of one particular feature allows of freedom in another direction, and latitude in one department may be partially compensated by greater care in another manufacturing operation. There is, in fact, no straight and narrow road to the production of a cheap and good cement, but a number of avenues leading to the same destination. Nevertheless, it is not to be supposed that the quality of Portland cement has reached its climax, nor has the cost of production reached its minimum, and the factors tending to high quality and low cost are kept continually in view by the manufacturer.

Lime in Cement

The quality of cement is controlled by the chemical constitution of the clinker from which the cement is made, the fineness of the cement, the gypsum content, and the absence of deleterious substances. The chemical analysis of a cement is not by itself a criterion of quality. Good burning of the clinker is essential. The meaning of "good burning" was found empirically, but it is now known that it really means that the clinker has been so burned that the amount of free lime in it is very small. Well-burned clinker also contains certain chemical compounds, some being crystalline and others solid solutions of crystalline compounds called "glass." Some of these compounds are responsible for the strength quality of the cement. The chief strength-giving crystalline compound is "alite," whose constitution is not yet definitely settled, but it is probably a solid solution of tri-calcium aluminate in tri-calcium silicate. To obtain the maximum amount of this compound, the amount of lime (CaO) in clinker must be as high as is compatible with the limits of CaO set by B.S.S. No. 12—1940. This reads as follows: "The percentage of lime, after deduction of that necessary to combine with the sulphuric anhydride present, shall not be more than 2.8 times the percentage of silica plus 1.2 times the percentage of alumina plus 0.65 times the percentage of iron oxide, nor less than two-thirds of that amount."

The fineness of the cement affects its quality insofar as early strength is concerned. Generally speaking, the finer the cement the greater the strength at early dates.

Gypsum affects quality in the following two ways: (1) The setting time of cement is controlled by the amount of gypsum which is ground with the clinker; (2) In the case of finely-ground cements, increases of gypsum up to the limit allowed by B.S.S. No. 12—1940 usually increase the early strength of the cement.

Certain substances are deleterious to cement. Many organic materials, such as cane sugar, destroy its setting and hardening properties even although they are present in minute quantities. Additions of most inorganic oxides and salts adversely affect the quality of cement.

Silica, Alumina, and Iron Oxide

The proportions of the other main constituents of cement, namely, silica, alumina, and iron oxide, may vary within certain limits. These constituents are usually calculated as ratios. The silica ratio is the ratio of the percentage of silica to the sum of the percentages of alumina and iron oxide, and is written

$$\frac{\text{SiO}_2}{\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3} \quad \text{or} \quad \frac{\text{SiO}_2}{\text{R}_2\text{O}_3}$$

In normal cements the range of useful values of this ratio are between 1.6 and 3.5, and good cements can be made from raw materials with silica ratios within this range provided that the alumina/iron ratio is a reasonable one.

The second ratio is the percentage of alumina to the percentage of iron oxide, which is written

$$\frac{\text{Al}_2\text{O}_3}{\text{Fe}_2\text{O}_3}$$

The range in the value of this ratio for normal Portland cements is between 1.6 and 3.5, but on the whole it is better to use, if possible, a lower ratio in this range than a higher one. B.S.S. No. 12—1940 gives a minimum permissible value of 0.67 to this ratio. Actually it uses the reciprocal $\frac{\text{Fe}_2\text{O}_3}{\text{Al}_2\text{O}_3}$ and gives the maximum value as 1.5, which means the same thing.

If the silica ratio is low, say, 1.6, and the alumina/iron ratio is also low, there is a risk of difficulty in burning due to excessive formation of molten glass.

Raw Grinding, Burning, and Clinker Grinding

The process of cement manufacture may be summarised under three headings :

- (1) The grinding of the raw material and mixing to the desired chemical composition ;
- (2) Burning in the kiln ; and (3) Clinker grinding.

The fineness of the raw material is important in relation to the production of good clinker in the kiln. If the raw mix is too coarse, incomplete combination of the lime, silica, alumina, and iron occurs, and, instead of the desired compounds, other compounds with quantities of free lime are produced and the cement quality is poor. On the other hand, the reduction of most raw material to excessive fineness is costly, and it is therefore desirable to use just that degree of fineness which will allow of complete combination in the kiln. The most suitable degree of fineness varies with the physical and chemical characteristics of the raw materials, and each manufacturer has to determine the limits of fineness requisite for his raw materials.

In a kiln using the wet process, drying the slurry, decarbonating the calcium carbonate, and burning at a high temperature to produce the requisite chemical compounds are all carried out in the same unit. The burning is taken to what is described as incipient fusion, i.e. part of the clinker is solid and part is liquid or molten glass. The solids are alite and di-calcium silicate, and the liquid is a solution of the other ingredients including lime, which is transferred at burning temperature

to the di-calcium silicate transforming it into tri-calcium silicate, which is the main constituent of alite—the chief strength-giving component.

When the clinker is cooled it is ground to a fine powder with a small quantity of gypsum to control the setting time. Generally, the finer the cement is ground the stronger is the resulting concrete at early ages. The fineness is controlled by B.S.S. No. 12—1940, by which the maximum residue permitted for ordinary Portland cement is 10 per cent. on B.S. sieve No. 170, and for rapid-hardening Portland cement 5 per cent. on B.S. sieve No. 170.

Cost of Production

Turning to the factors which influence the cost of production, the first great controversy is the wet versus the dry process. The arguments on both sides are numerous, and they introduce subsidiary questions such as the effect on quality, the value of waste-heat boilers in both wet and dry processes of manufacture, whether effective dust-collection from kilns is economically possible, etc.

The discussions as to the type of kiln to be favoured are becoming less intense, and except under very unusual conditions no other but the rotary kiln is recommended for present-day conditions which demand high quality, minimum employment of labour, and large manufacturing units. But the best dimensions for rotary kilns remain a subject upon which many different opinions could be cited, each with a basis of sound experience. There is, moreover, a greater prospect of economy in rotary kiln operation than in the other departments of manufacture, and it is naturally a matter of prime interest until the necessary evidence is available to decide the net advantages of the short kiln, the long kiln, the kiln with the enlarged burning zone, the enlarged calcining zone, the enlarged slurry zone, or other special features which have to be settled by the raw material to be dealt with.

The type of coal to be used in rotary kilns is frequently settled by considerations of price, but in some cases there is a choice between coal with a high volatile content and a low volatile content, or between low-priced coal with much ash and an expensive coal of high calorific value; there are advocates for each of these alternatives, and a decision must depend upon the cost at which the required heat can be produced. The degree of fineness of coal grinding is bound up with the quality of coal, and in turn introduces the question of the best type of mill for coal grinding—the unit pulveriser, the tube mill, or the pendulum mill. The bugbear of clinker rings and their disastrous effect upon continuity of kiln operation is also related to coal quality and fineness, and needs to be considered in connection therewith.

The rotary kiln lining is a problem of recent origin. In England the ordinary English firebrick was the only one available until a few years ago, when foreign bricks containing over 60 per cent. of alumina were imported. The works manager now has to decide whether these high-priced aluminous bricks are worth while. Does it pay to use a common firebrick with a life of four months rather than an aluminous brick at three times the price and with a prospect of a much longer life?

For the utmost economy a rotary kiln must run continuously and with the minimum coal consumption, but then the question arises whether the output per running hour can be economically increased to an extent involving additional fuel consumption per ton of clinker; and again whether a high running output necessarily connotes a high fuel consumption.

Usually the desirability of installing labour-saving appliances in a cement works is a foregone conclusion. Means of transport of material constitute a large proportion

of such appliances and the makers of various types of conveyors and elevators, mechanical and pneumatic, have a wealth of argument which frequently makes decision difficult.

With regard to power in cement factories, the present tendency is towards complete electrification and the purchase of electricity. The absence of a power plant on a cement factory removes a burden from the manager's shoulders and reduces the capital expenditure per ton of annual output.

Sufficient has been written to indicate that although cement manufacture is simple in principle, comprising two processes of grinding and one of heating, the details of the operations have such diverse possibilities that there is scope for much discussion.

The cost of production of Portland cement, apart from selling costs, depends mainly upon five items, viz. capital expenditure; labour and supervision; fuel; power; and renewals and repairs.

The construction costs of a new factory will depend upon many factors, the first of which are the locality in which it is to be erected and the nature of the site, followed by other considerations such as the type of plant and machinery chosen, the class of buildings to be erected, the nature and amount of storage to be provided for coal, raw materials, clinker, and cement, whether power is to be generated or bought, and so on. As already stated, the modern trend is in the direction of the all-electric drive with power purchased from central generating stations, and this arrangement very substantially reduces the capital required per ton of annual output for the equipment of a new cement works.

In most cases the relative advantages of reduced capital costs or reduced running costs may call for a very careful review of details before a decision can be reached on the course likely to prove most economical in the long run. Broadly speaking, however, the general high level of wages in the English cement industry to-day requires that labour-saving appliances shall be adopted to the fullest extent, even in cases where little advantage could formerly be shown.

In view of the present-day wages which are normally payable for overtime and week-end work, and the increasing tendency to restrict hours of labour, it will often be found good policy to equip the raw material, clinker-grinding, and despatch departments on a scale which will enable the output of the kilns to be dealt with during a much less period than the full 168 hours of a week which the kilns must necessarily be run. This entails increased capital expenditure for additional machinery in the departments concerned which will only be productive for a part of the week, but the cost of this may be more than offset by economy in running costs.

The three chief items of works running costs are labour and supervision, fuel, and power. The first two normally comprise about half the total factory costs, and the cost of power about half of either of them. Repairs and renewals are a heavy item. In addition to the factory cost the total cost of production must include administration and sales costs, insurances, rates and taxes, depreciation and obsolescence of plant, as well as reserves and losses—generally an item as large as any other in the cost of production. The subject of factory costs can, however, only be generalised upon; since the specific data upon which costs can be calculated vary considerably according to circumstances such as position, raw materials, and tonnage output.

Of the factors which may influence the cost of production, the first is the question of the wet versus the dry process. The arguments in favour of both are numerous,

and they introduce subsidiary questions such as the effect on quality. A decision is, however, usually influenced very largely by the nature of the raw materials, and the pros and cons of this are dealt with in a later chapter.

For reasons already given, no other than a rotary kiln plant would be normally recommended for modern conditions which demand high quality, minimum labour, and large manufacturing units, although the best dimensions for such kilns is a subject upon which different opinions are held. This subject will also be dealt with in a future chapter, but the decision affects both capital and production costs. When all these questions have been decided there are many others of perhaps less importance which will affect manufacturing costs in some degree.

The factors which enter into manufacturing costs may be summarised as follows :

- (1) RAW MATERIALS : Cost of chalk or limestone.
Cost of clay or shale.
- (2) LABOUR : Manufacturing.
Repairs.
Packing and shipping.
- (3) FUEL for drying and burning.
- (4) POWER.
- (5) OTHER SUPPLIES, ETC. :
Gypsum.
Machinery parts and stores, including lubrication.
Haulage and transport.
Miscellaneous (upkeep of buildings, permanent way, lighting, etc.).
- (6) OVERHEAD CHARGES :
Administrative and management expenses, including office,
laboratory, etc.
Depreciation and obsolescence of plant and machinery.
Rates and taxes.
Insurances.
Depletion of raw material reserves.

(1) RAW MATERIALS.—The cost of raw materials differs within wide limits between one plant and another. Factors affecting it are royalties payable, the nature and accessibility of the deposit, its hardness, the amount of overburden, the depth available (particularly above water level), and its proximity to the works. A hard stone which requires drilling and blasting before it can be handled will necessarily cost more per ton than soft material which can be dug direct with a digger. Again, as the removal of overburden is an unremunerative operation it adds to the cost in proportion to its depth.

If there is little material available above water level it may be necessary to go lower, in which case the cost of continued pumping is incurred except in the case of clay or soft chalk which can be dug below water. If the quarry is reasonably close to the works it may be found convenient to erect the crushing or washing plant in the quarry, and when the wet process is adopted the slurry can be conveniently pumped to the works. On the other hand, it may be necessary to load the materials into trucks or vessels and convey them for long distances.

(2) LABOUR.—Unless labour is exceptionally cheap, hand labour must be replaced by machinery in every department, and an output of two tons or more per day for every man employed on manufacturing operations may be looked for on a

modern plant. This takes no account of men employed on repair work or on packing and shipping, and is of course only an approximate guide. It varies with the arrangement and equipment of the factory, and especially in cases where raw material or power may be purchased.

(3) FUEL.—The type of coal to be used is usually settled by considerations of price; this particularly applies to the coal used for burning, where something like one-quarter of the works cost of manufacturing cement is incurred. Some coals are so high in ash content, or otherwise unsuitable, that they are not satisfactory no matter how cheap they may be. In England bituminous coals of fair quality are so readily obtainable that price becomes the final arbiter, and this in turn is affected by the relative positions of cement works and collieries and the means and cost of transport. In the best modern practice not more than 5 cwt. of coal of 12,600 B.T.U.'s per lb. are used for burning a ton of cement on the wet process, and approximately 1 cwt. less per ton on the dry process. Oil is not used in British works as its cost is high in comparison with coal.

(4) POWER.—Coal for power is usually of a more specialised character, depending upon the type of power plant, and as the tonnage required is so much smaller than that used in burning the higher cost of the selected quality is not of such serious import. If waste-heat boilers are installed and power is obtained from the kiln gases, then the quantity of power coal required is further reduced.

Where electric power is purchased its cost is usually on a sliding scale subject to coal prices and other factors. Agreements for such supplies customarily contain provisions for peak and minimum loads, and in designing a new plant a careful balancing of units should be made in order to secure a constant load factor.

(5) OTHER SUPPLIES, ETC.—Gypsum, stores, lubricating oils, etc., are usually purchased and costs can be calculated fairly accurately as a rule. About 4 per cent. of raw gypsum stone is likely to be used. Some cement works have contracts under which their requirements of lubricants are supplied at a fixed price per ton of cement produced.

Haulage and transport, again, are much influenced by the situation of the works in relation to raw materials and markets.

Machinery repairs and replacements are usually a heavy item, and the saving which can be effected under this head in designing a new plant is often considerable. The item, of course, tends to rise in every plant as time passes, and cement works machinery, notwithstanding its robust construction, has a relatively short life.

(6) OVERHEAD CHARGES.—The cost of administration and management is usually in inverse ratio to the output; the larger the plant the less the cost per ton under this head.

Rates, taxes, and insurances may amount to as much as 6 to 8 per cent. of the manufacturing costs.

Allowances for depreciation and obsolescence of plant and machinery should be at least 5 per cent. of their first cost, and may well be 10 per cent. in some cases if a sound and conservative financial policy is pursued.

Charges for raw materials depletion and reserves will depend upon very variable factors, and must be determined separately in each case.

CHAPTER III

RAW MATERIALS

ANY raw materials which will yield by calcination the silicates, aluminates, and ferro-aluminates of lime which form the chief components of Portland cement may be used. Lime, which is usually in the form of carbonate of lime (such as chalk and limestone), silica, alumina, and iron oxide are necessary, and the latter are generally found in clay or shale in a combined form. Marls, calcareous tufa, blast-furnace slags, alkali waste, etc., also contain indefinite proportions of lime, silica, and alumina, and these materials are also used in cement manufacture, although only to a comparatively small extent.

In manufacturing high-alumina cements, which are not included in the category of "Portland" cement, the constituents are chiefly an aluminate of lime made up of about 40 per cent. lime, 40 per cent. alumina, and 20 per cent. silica, iron oxide, and other ingredients, the raw materials used being chalk or limestone and bauxite.

On the other hand, pozzolanic cements, once used by the Romans, consist sometimes of volcanic tufas, which are of a porous open-grain structure, mixed with slaked lime, and these produce a durable cement used by the ancients for their building constructions. These pozzolanic materials alone do not produce a cement; the presence of a cementing addition is a necessity, while the activity of the ground volcanic material depends on the presence of soluble silicic acid or hydro-silicic acid which enters slowly into combination with the lime hydrate. For this reason any material furnishing silicic acid readily available for reaction with a strong base such as lime may be used for pozzolanic cement. Even dehydrated silicate of alumina, or lightly-burnt clay, will act sufficiently to form with lime hydrate a cement which is sometimes applied practically by mixing brick dust with slaked lime and which results in a kind of hydraulic mortar.

A modern kind of artificial pozzolanic cement has found application in the form of a slag cement made from granulated blast-furnace slag ground together with quick-lime or lime hydrate. Blast-furnace slag cooled slowly represents an artificial basic material with but slight hydraulic properties. When granulated or cooled quickly in the liquid condition by means of cold water, it possesses the characteristics of a natural pozzolana and has considerable soluble or available silicic acid, and when intimately mixed with lime hydrate produces an hydraulic cement.

White hydraulic cement, again, is prepared from kaolin and chalk with silica in some form or other, these materials being practically free of iron.

In the case of "natural" cements, by which are meant cements made from natural intimate mixtures of calcium carbonate and clay in their occurring geological formation, these materials are burnt, as dug, at a high temperature, and produce an hydraulic cement.

Rapid-hardening cement is actually a superfine Portland cement.

Given the clean carbonate of lime content as the greater preponderating ingredient in the raw materials used in the manufacture of hydraulic cements, the "clay" content can be a complex mixture of minerals, provided its analysis is correct and that there is little free crystalline silica present.

The primary and sedimentary classes of clay, whether kaolins or shales (alluvial or glacial), are all found to be more or less of use provided there is no deleterious content, the choice depending upon proximity of the materials to the carbonate of lime deposit.

In cases where the prevailing conditions demand the addition of silica as such to a Portland cement raw material mixture, and it becomes necessary to look for a siliceous material, then such material must be fine or easy to grind to an extremely fine flour if it is to be satisfactory for the purpose; sometimes such materials are made more easily reducible by being heated and quenched while hot by a stream of cold water, a good red heat in the kiln being sufficient to accomplish the desired result.

In lias limestone and chalk-marl deposits the necessary ingredients are found in approximately sufficient proportions for cement manufacture in the one deposit, already naturally mixed, but rarely, if ever, in the exact proportions required. Cements could be made cheaply by the simple method of burning lumps of material as quarried, and then grinding the clinker, if a geological formation uniformly composed, and with the exact proportions of carbonate of lime, silica, iron, and alumina, could be found. There are, however, no such deposits in Great Britain, at any rate in quantities sufficiently large to warrant their use without careful mixing. It has to be remembered that a variation of even 0.5 per cent. of the amount of carbonate of lime in the raw materials, as well as variations in the other ingredients, will result in inferior quality cement. It is necessary, therefore, that the raw materials be correct in chemical composition if they are to be suitable for Portland cement manufacture. In Great Britain a percentage of not more than 4 of magnesium is permitted, and it is essential that free or insoluble silica in the form of chert, flint, or quartz should not be present at all, or at any rate only in very small amounts. The proportion of sulphuric anhydride should not be more than 2.75 per cent. While iron oxide and alumina are necessary for fluxing during calcination, an excess of either of these substances is to be avoided.

It will be obvious that it is not always possible to find on the same site the two principal materials necessary for the manufacture of cement. All the most successful factories are built on sites where the necessary raw materials are found locally and coal may be obtained at a cheap price.

Whilst it is not absolutely essential that the raw materials should be soft and pure, this is an advantage as it leads to economy in excavating, crushing, and mixing the materials.

The amount of raw materials necessary for a plant using dry materials (such as a mixture of limestone and shale) is about 16,000 tons a year for the production of 200 tons of cement a week. The total includes about 4,000 tons of shale and about 12,000 tons of limestone. A cubic foot of limestone weighs approximately 160 lb., so that 168,000 cu. ft. of limestone a year are required to produce 200 tons of cement a week. A cubic foot of shale will contain approximately 125 lb. of dry material, as shale invariably contains a considerable amount of water; 72,000 cu. ft. of shale will therefore be required each year for an output of 200 tons of cement a week. Thus at least 3,360,000 cu. ft. of limestone and 1,440,000 cu. ft. of shale will be needed for a factory producing a weekly output of 200 tons of cement if there are to be sufficient raw materials available to keep the plant running for twenty years.

In selecting a site for a cement factory, in addition to the supply of raw materials such questions as fuel supply, distance from the principal points where the cement

is to be used and facilities for delivery by road, rail, or water, have also to be considered.

The composition of a prepared mixture of the raw materials would be approximately three parts of chalk or calcareous constituent with the balance of clay or argillaceous or other constituent to make up the correct mixture to produce a good quality Portland cement. The analysis of a mixture of raw materials for the manufacture of cement may be, as an instance, somewhat as follows :

	Per cent.
Carbonate of lime	76.35
Silica	14.46
Alumina	5.33
Ferric oxide	1.69
Magnesia	0.04
Sulphuric anhydride	0.31
Potash, soda, etc.	1.82

100.00

Great Britain

THAMES AND MEDWAY.—The chalk found near the river Thames, and Thames mud or clay, were first used in an experimental way for the manufacture of cement so far back as the year 1820, and it was shortly after this date that the first cement factory on the Thames was erected at Northfleet. A good supply of raw materials suitable for the manufacture of cement is found in the chalk formation of the banks of the Thames and Medway, and the mud in the banks and creeks of these rivers.

The following are typical analyses of these materials :

	Chalk. (per cent.)	River mud (per cent.)
Silica	1.52	65.02
Alumina	} 0.85	19.74
Ferric oxide		7.22
Carbonate of lime	96.45	1.52
Loss, etc. (and organic matter)	1.18	6.50
	100.00	100.00

White chalk (containing about 18 per cent. of water) on the Thames, and the grey or lower chalk underlying the white chalk in the neighbouring hills of the Medway, for a long time were the only materials used, together with clay, in cement manufacture. Most of the clay found in the Thames and Medway valleys is alluvial mud reclaimed from the banks of the estuaries, from what are known as "saltings." The Thames and Medway deposits of chalk are anything from 100 ft. to 300 ft. working depth. Mechanical plant is invariably used for excavating it, and locomotives and trucks are used for transporting it from the quarries to the factories. In some cases the material is washed at distant quarries and pumped to the factories.

LIAS LIMESTONE FORMATION.—Manufacturers in the Rugby and South Wales districts where Portland cement is made use the lias formation of limestone and shale, which has to be very accurately proportioned on account of the thin layers in which it occurs and the great variation in its composition. In other parts of the country similar deposits are found, but in most cases the proportion of shale is so much greater than the limestone that the cost of operating these deposits would be excessive. In many cases the limestone contains from 80 to 85 per cent. of carbonate of lime. In the Rugby and South Wales districts good quality Portland cement is produced from these raw materials, sometimes by the dry process.

As a rule the thickness of the shale beds is considerably more than that of the limestone. The layers of impure limestone vary in thickness from 2 in. to 2 ft. or more, separated by shale or clay comprising the lias formation. In the following table analyses are given of the lias limestone and shale :

	Limestone. (per cent.)	Shale. (per cent.)
Silica	7·81	30·05
Ferric oxide	1·90	3·35
Alumina	2·59	10·70
Calcium carbonate	84·37	46·88
Magnesium carbonate	1·72	3·68
Alkalis and loss	1·61	5·34
	<hr/> 100·00	<hr/> 100·00

CAMBRIDGESHIRE.—In the neighbourhood of Cambridge a deposit of chalk marl consisting of calcareous and argillaceous material already naturally mixed is found below the local chalk, its principal variation from the chalk above it being in the quantity of clay it contains. It is interesting to note that although the relative qualities may vary throughout the depth of the face of the quarry it is found that the proportion of calcareous and clayey matter is about the same as is obtained in the Thames and Medway valleys by mixing chalk with alluvial mud. In the most favourable conditions this deposit is situated some 2 ft. below the surface, and extends to a depth of from 30 ft. to 60 ft. Various analyses show that the quantity of chalk in the deposit averages from 70 to 80 per cent. of the total, while it is rather remarkable that the amounts of silica, alumina, and oxide of iron forming the remainder of the deposit are in the right quantities required for making cement. It will be realised that a deposit such as this has to be treated carefully, and as a matter of fact what is known as the “lower chalk” marl is blended with the material containing an excess of lime-carbonate, producing a working average of about 76 per cent. of calcium carbonate. So near do these deposits approach the correct constituents for cement manufacture that at one time some of the Cambridgeshire marl deposits were used for making “natural” cement without mechanical mixing. The calcareous deposit was burnt as excavated, and the clinker ground. Owing to the unreliable quality of cement produced in this manner it is not surprising that the process was long ago discarded.

Owing to their freedom from stone and flints Cambridgeshire marls are suitable for mixing by either the wet or dry process. From these deposits, when corrected and properly mixed, an excellent cement may be manufactured, equal in quality

PORTLAND CEMENT

to the best Portland cement. An analysis of mixed raw materials for the manufacture of cement from the Cambridgeshire deposits is as follows :

	Per cent.
Silica	15.72
Alumina	4.20
Ferric oxide	1.89
Calcium carbonate	76.60
Magnesium carbonate	1.31
Undetermined	0.28

100.00

NORTH OF ENGLAND AND MIDLANDS.—In the North of England, Portland cement is generally manufactured from chalk obtained in the neighbourhood, mixed with a good clay which contains less organic matter than that used in the south. A good quality cement is made from this mixture. In Hull the chalk deposits on the banks of the Humber are used with local clays. In Northamptonshire the oolite limestone and lias clay, which are sometimes superimposed one above the other, are used as raw materials.

SCOTLAND.—Near Edinburgh a deposit of comparatively pure crystalline limestone mixed with lower grades of stone has been used, and at other Scottish works blast-furnace slag and limestone are used as raw materials.

IRELAND.—A deposit of indurated chalk (locally termed "limestone") is employed near Larne for the manufacture of cement, and is intimately mixed with clay dredged from Lough Larne. The composition of these materials is :

	Limestone. (per cent.)	Clay. (per cent.)
Silica	0.85	49.47
Alumina	0.51	14.66
Ferric oxide		6.81
Calcium carbonate	97.86	Lime 6.35
Magnesium carbonate	0.70	Magnesia 3.02
Alkalis and loss	0.08	2.78
Loss on ignition	—	16.91

The above descriptions cover the most important deposits of cement raw materials in Great Britain. Other calcareous deposits are also used in Eire.

Europe

FRANCE AND BELGIUM.—In France chalk and clay are the raw materials generally adopted, while in Belgium a low-limed limestone is used.

GERMANY.—In Germany bluish-grey and white limestones and marls are used. In some parts the raw material consists of argillaceous limestone from the Muschelkalk deposits, which in parts are hard and dark coloured, and also very shattered, and contain on an average about 91.26 per cent. of carbonate of lime. The clay used is of a gault variety.

SPAIN.—There are in Spain abundant supplies of raw materials, which in parts are almost unique, comprising a calcareous loam, homogeneous and containing 72 per cent. calcium carbonate, and also an amorphous carbonate of lime in the state of a very fine powder containing 97 per cent. of calcium carbonate. In some parts

of Spain the raw materials consist of a hard crystalline mountain limestone, both pure and low-limed, to which it is sometimes necessary to add sandstone and clay to provide the necessary silica and alumina content to the pure limestone. Trass, volcanic ash, and scoria are also found and used in Spain for the manufacture of a pozzolanic cement.

DENMARK.—A soft chalk without flints is found here with about 98 per cent. CaCO_3 . Alluvial clay from saltings is used in conjunction with this chalk.

DALMATIA.—Large deposits of marl exist all along the Dalmatian coast, the vast majority of them being practically washed by the sea. The outstanding feature of these deposits is that the quality of the marl is so comparatively regular that it is often burnt without any preparatory treatment. The value of this raw material for the manufacture of cement lies in the fact that it is a natural mixture of clay and limestone, containing about 75 per cent. of carbonate of lime and over 20 per cent. of clay, but the natural analyses limit the quality of the resulting cement unless carefully proportioned before mixing. The following are analyses of typical samples :

	Light, (per cent.)	Dark, (per cent.)
Silica	13.06	12.46
Alumina	5.73	5.93
Ferric oxide	1.13	0.93
Lime	41.71	41.93
Magnesia	1.28	1.39
Sulphuric anhydride	Nil	Trace
Loss on ignition	36.32	36.40
Alkalis and undetermined	0.77	0.96
	100.00	100.00
Calcium carbonate	74.48	74.87

Limestones exist also in large quantities, but are sometimes of a siliceous nature.

America

UNITED STATES.—A great deal of the United States cement production is from the argillaceous limestone of the Lehigh Valley. This often contains more clay than is desirable for a correct mixture. Usually 10 to 20 per cent. of pure limestone is added to give the necessary percentage of calcium carbonate. Oyster and sea shells and marl also are employed for the carbonate of lime content.

CANADA.—In Canada and British Columbia the high and low-limed hard limestones and marls are similarly used.

MEXICO.—Extensive deposits of clay and crystalline limestone exist in Mexico and the following are typical analyses

	Clay, (per cent.)	Limestone, (per cent.)
Silica	40.38	3.20
Alumina	15.90	1.55
Ferric oxide	4.00	0.80
Lime	11.90	51.90
Magnesia	3.98	1.14
Sulphuric anhydride	0.41	1.48
Loss on ignition	14.80	39.85
Undetermined	2.63	0.08
	100.00	100.00

India

Extensive deposits of limestone are found in India of very suitable composition, so that no further addition of argillaceous material is needed for cement manufacture. This stone is classified into two varieties : one variety contains calcium carbonate between 78 and 86 per cent. and is known as " high limestone," and the other contains calcium carbonate between 70 and 77 per cent. and is known as " low limestone." Typical analyses of the two limestones are as follows :

	High limestone. (per cent.)	Low limestone. (per cent.)
Insoluble matter		
Silica	8.48	22.08
Ferric oxide		
Alumina	3.88	4.48
Lime	46.66	39.71
Magnesia	2.02	0.94
Loss on ignition	38.56	32.76
	99.60	99.97

Clay is found in very large quantities, but in places is not used to a great extent owing to the suitable composition of the limestone.

In other parts of the country the silica content of the limestone and clay is insufficient, and this is augmented by the addition of a siliceous stone with a typical analysis as follows :

	Per cent.
Silica	69.60
Ferric oxide	8.30
Alumina	14.88
Lime	3.30
Magnesia	0.65
Loss on ignition	0.80
	97.53

Deposits of laterite are available for the manufacture of a cement high in alumina.

South Africa

The deposits of limestone in South Africa vary in texture in different regions. Some consist of a secondary white noduled and concretionary limestone, coherent above with soft powdering stone below, with a mixture of white and earthy marl and clay intrusions together with shale lumps and some stones of hard blue limestone with pyrites crystals. In other parts the " limestone " includes a hard and massive tufa. The quality also varies from a siliceous material of small value to a limestone of high purity, of which latter material large quantities exist. The content of magnesium carbonate, however, often varies considerably, ranging from nothing to as much as 30 per cent. in some of the limestone. A friable rufous alluvium is also available. The average percentage of calcium carbonate in the chosen limestone is generally about 76 and of carbonate of magnesia 5. The clays contain an average of 51 per cent. silica and about 11 per cent. alumina, and in places they are found to

be low in magnesia. The shale consists of hard siliceous stone which is sometimes found to be very low in iron and alumina.

Australia

Among the raw materials used in Australia are limestone and marine shales, consisting almost entirely of silica and alumina deposited as the silt of an ancient sea bed. Limestone occurs in great deposits in parts, but in many places is not sufficiently pure to be used for cement manufacture. Many of the deposits such as are to be found in Australia were, by great upheavals of the earth's surface, tilted until practically standing on edge, with the result that what is now the vertical face was originally the bed as deposited; this accounts for the great depth to which limestone deposits sometimes extend, but they are also sometimes mixed with intrusions. The quality of the limestone in places is excellent, containing between 93 per cent. and 96 per cent. calcium carbonate. Shale is also available in abundance.

China and Japan

Excellent limestone and clay are found in parts of China. In parts of Japan, limestone and clay are found as well as natural cement rock, but the quantity of the latter is very small. Natural volcanic materials (pozzolana) are found in profusion in several parts of the country and are used very generally.

Malay

In Malay there are plentiful supplies of limestone, clay, and sand, but the stone is principally a blue magnesian limestone. Occasionally among this material occur patches of good crystalline limestone, but the quantity of magnesia in this varies as will be seen by the following analyses :

	Per cent.	Per cent
Lime	55.00	51.40
Magnesia	0.29	3.13
Ferric oxide }	0.40	0.26
Alumina }		
Silica	0.44	0.60
Loss on ignition	43.62	43.50

Some of the limestone found in Malay is highly dolomitic.

In Singapore, coral is used to obtain the necessary calcium carbonate. The clay used for incorporation with the coral is blue-grey estuarine mud.

These are a few instances only of the wide range of raw materials now used, and they indicate that, provided the correct constituents are found, and that no deleterious matter is allowed to be included, the manufacture of Portland cement depends solely upon the careful and accurate choice and treatment of the constituents for the preliminary process of the manufacture. It will be seen that given calcium carbonate and suitable clay, or other substitute, in approximate proportions of about 3 to 1, or lime with silica and alumina in any other form but accurately proportioned, it is most important that the materials be treated with a complete knowledge of the chemical and mechanical operations of combining them, as this alone can secure the regular manufacture of a reliable product.

As stated, the suitability of the raw materials depends primarily upon the manner of the occurrence of these requisites, the position of the materials with respect to the area in which the cement is to be sold, and fuel supplies, for since with every ton of cement manufactured there will be used nearly half a ton of coal or other fuel, the location of the factory in regard to cheap fuel supplies is an important factor.

Proportioning the Raw Materials

When geological deposits of suitable composition have been secured, the next step is to calculate the required proportions of the raw materials. In the British Standard Specification for Portland Cement, No. 12—1940, the maximum lime (CaO) permissible in Portland cement is based on the theory of Dr. F. M. Lea and Dr. T. W. Parker.* In this specification "the percentage of CaO (in cement), after deducting CaO necessary to combine with SO_3 , shall not be more than 2.8 times the percentage of SiO_2 plus 1.2 times the percentage of Al_2O_3 plus 0.65 times the percentage of Fe_2O_3 ,"† or

$$\text{Max. CaO (\%)} = 2.8 \text{ SiO}_2 + 1.2 \text{ Al}_2\text{O}_3 (\%) + 0.65 \text{ Fe}_2\text{O}_3 (\%) \quad (1)$$

It is convenient to express the actual CaO content as a percentage of the maximum CaO permitted by this equation, e.g. if the maximum CaO according to the equation is 69.5 per cent. and the actual is 66 per cent., then the percentage saturation is

$\frac{66}{69.5} \times 100 = 95$ per cent. If, therefore, it is desired to calculate the analysis of clinker from given raw materials the following procedure may be adopted.

Assume that the analyses of the raw materials (chalk and clay) are as follows :

	Chalk (per cent.)	Clay (per cent.)
SiO_2	0.4	56.3
Al_2O_3	0.2	21.4
Fe_2O_3	0.3	4.5
CaO	54.8	2.4
MgO	0.7	1.6
Loss on ignition	43.2	9.4
Alkalis, etc.	0.4	4.4
	<hr/>	<hr/>
	100.0	100.0

It is necessary to decide on the degree of saturation required in the clinker. It is convenient to take this at 100 per cent. and allow the fuel ash to reduce the CaO somewhat below the maximum allowed, and this is usually adopted for simplicity. To illustrate the method more generally, suppose that 95 per cent. saturation is desired without allowing for fuel ash, then the constants in equation (1) are :

$$\begin{aligned} \text{Lime saturation} &= 2.8 \times \frac{95}{100} \text{ SiO}_2 (\%) + 1.2 \times \frac{95}{100} \text{ Al}_2\text{O}_3 (\%) + 0.65 \times \frac{95}{100} \text{ Fe}_2\text{O}_3 (\%) \\ &= 2.66 \text{ SiO}_2 (\%) + 1.14 \text{ Al}_2\text{O}_3 (\%) + 0.62 \text{ Fe}_2\text{O}_3 (\%) \end{aligned}$$

The next stage in the calculation is due to the fact that in both the chalk and clay there are quantities of CaO, SiO_2 , Al_2O_3 , and Fe_2O_3 . In both, therefore, there

* Lea and Parker. The Quaternary System, $\text{CaO}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{Fe}_2\text{O}_3$ in relation to Cement Technology. Building Research Technical Paper No. 16, 1935.

† B.S.S. No. 12-1940. Section 9, p. 8.

are already certain proportions of potential clinker of the desired lime saturation. The amounts can be calculated as follows :

Chalk	Clay
$\text{SiO}_2, 0.4 \times 2.66 = 1.064$	SiO_2 required for CaO
$\text{Al}_2\text{O}_3, 0.2 \times 1.14 = 0.228$	$= 2.4 \times \frac{1}{2.66} = 0.9$
$\text{Fe}_2\text{O}_3, 0.3 \times 0.62 = 0.186$	$\text{CaO} \quad \quad = 2.4$
$\text{CaO} \quad \quad = 1.478$	Potential clinker . $= 3.3$
$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 = 0.900$	
Potential clinker $= 2.378$	

CaO must now be allocated to the argillaceous material left in the clay after subtracting the amount of SiO_2 required for the potential clinker.

Clay	
$\text{SiO}_2, 55.4 \times 2.66$	$= 147.4$
$\text{Al}_2\text{O}_3, 21.4 \times 1.14$	$= 24.4$
$\text{Fe}_2\text{O}_3, 4.5 \times 0.62$	$= 2.8$

Total CaO required per 100 parts of clay $= 174.6$

The amount of CaO required for the potential clinker in the chalk must be subtracted from the CaO content of the chalk. This leaves 53.32 per cent. CaO available in the chalk for combining with the available argillaceous materials in the clay. One hundred parts of clay require 174.6 parts of CaO ; therefore the parts of chalk required for the clay are $\frac{174.6}{53.32} \times 100 = 327.4$. The mixture required is therefore 1 part clay and 3.274 parts chalk.

In order to calculate the amount of clinker obtained from this mixture, the various amounts of SiO_2 , Al_2O_3 , etc., in the constituents are added together as follows, with the assumption that one-fourth of the total alkali present in the raw material is driven off in the kiln.

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Alkalis, etc.
Clay	56.3	21.4	4.5	2.4	1.6	3.3
Chalk	1.3	0.7	1.0	179.4	2.3	1.0
	<hr/> 57.6	<hr/> 22.1	<hr/> 5.5	<hr/> 181.8	<hr/> 3.9	<hr/> 4.3

This adds up to 275.2, showing that 1 part of clay and 3.274 parts of chalk give 2.752 parts of clinker.

The ash in the coal has still to be accounted for, and this may be done as follows. A typical British coal used for rotary kilns has (say) 10 per cent. of ash of the following composition :

SiO_2	.	.	.	45 per cent.
Al_2O_3	.	.	.	30 "
Fe_2O_3	.	.	.	15 "
Rest	.	.	.	10 "

The coal consumption may be assumed to be 27 per cent., and it is usual for about 65 per cent. of the ash to be taken up by the clinker, the remaining 35 per cent. going to the dust chamber and the chimney. The amount of ash will therefore be $27 \times 0.65 \times 0.1 = 1.75$ parts per 100 parts of clinker. This may now be added to the constituents of the clinker from the chalk and clay, after multiplying each component of the ash given in the analysis by $0.0175 \times 2.752 = 0.048$.

	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Alkali, etc.
Clinker from chalk and clay .	57.6	22.1	5.5	181.8	3.9	4.3
Ash	2.2	1.4	0.7			0.5
	59.8	23.5	6.2	181.8	3.9	4.8

This corresponds to 280 parts of clinker including ash, and it is obtained by burning a mixture of 100 parts of clay and 275.2 parts of chalk. Reducing these proportions to a basis of 100 gives the composition of the resultant clinker as follows :

SiO ₂	.	.	.	21.4	per cent
Al ₂ O ₃	.	.	.	8.4	"
Fe ₂ O ₃	.	.	.	2.2	"
CaO	.	.	.	64.9	"
MgO	.	.	.	1.4	"
Alkali, etc.	.	.	.	1.7	"
				100.0	"

From equation (1) the maximum CaO permitted by B.S.S. No. 12-1940 will be found to be 71.3 parts, hence the final CaO saturation is $\frac{64.9}{71.3} \times 100 = 91$ per cent.

The method described is the most modern procedure in the determination of the proportions of raw materials to use for the production of clinker complying with B.S.S. No. 12-1940. In the earlier editions of the B.S.S. the method was simpler, as the maximum CaO was indicated by assuming that all the SiO₂ and Al₂O₃ are in the forms 3CaO.SiO₂ and 3CaO.Al₂O₃. The lime ratio of the earlier British Standard Specifications was obtained from the molecular formula $\frac{\text{CaO}}{\text{SiO}_2 + \text{Al}_2\text{O}_3}$ not greater than 3. For the clinker analysis previously given this would therefore be $\frac{64.9}{56} \div \left(\frac{21.4}{60} + \frac{8.4}{102} \right) = 2.644$. This older method is naturally more familiar to cement chemists, who will no doubt continue for some time to think in terms of this lime ratio. For such, it may be interesting to note that for nearly all British cements the new lime-saturation figure can be found approximately by multiplying the lime ratio by 34, e.g. for clinker as previously described: lime ratio = 2.644 \times 34 = 90 per cent. saturation, compared with 91 per cent. actual.

Winning Raw Materials

The methods of winning raw materials are determined by several factors, such as the location of the strata in reference to the natural level of the surrounding country, the hardness of the material, the thickness of the strata, the probable presence of useless overburden, etc. In some cases the strata of the desirable material

are waterlogged, and the choice then lies between digging the materials as they lie under water or pumping away the water.

If the cement works is small it may be doubtful, even with relatively high labour costs, whether the installation of mechanical tools is economical, as the somewhat high capital and maintenance costs are a heavy charge on small outputs. Where, however, weekly quantities of over 1,000 tons are required, suitable mechanical appliances are usually more economical, and in addition to the cheaper cost of operation they enable the work of quarrying to be carried on in wet weather, which could not be done easily and safely in the case of hand labour.

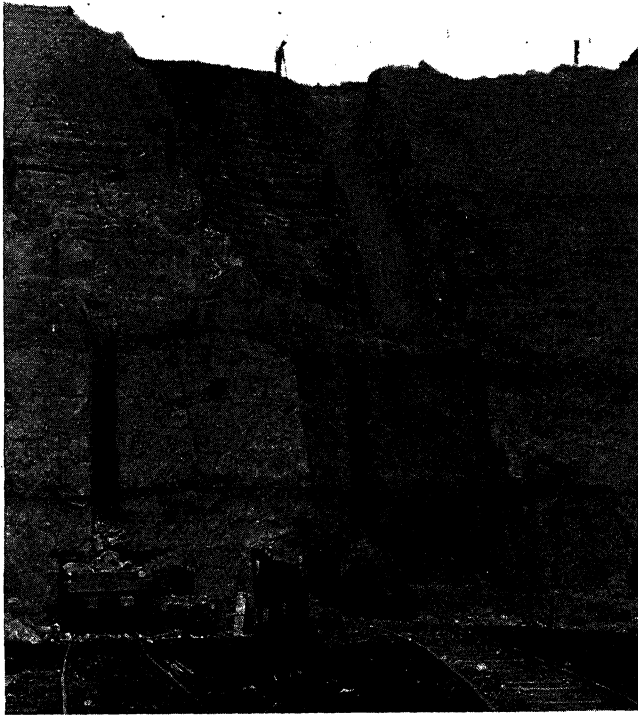


Fig. 2.—Milling Chalk by Hand.

Before the introduction of mechanical appliances in the early years of the present century, the softer materials such as chalk, marl, and in many cases clay, were obtained by what is known as "milling" (see *Fig. 2*) which was carried out by working back the quarry face at a fairly steep slope for a height of 30 to 100 ft. or more, according to circumstances. The bottom of the face was worked to a narrow outlet, at which a truck was placed. The quarrymen stood on small benches which they made in the face of the cliff, and with pointed bars loosened the material which rolled down the sloping face and converged on the narrow outlet and so fell into the truck. This method is one of the most economical ways of digging this class of raw material by hand, as, given suitable conditions, it is possible for a man

to dig and put into trucks as much as three tons per hour. The whole of the face cannot be dug at this speed, as anything below the top of the truck must be lifted into it. Mechanical picks are now used for this form of digging.

The method of digging raw materials generally used now is with the excavator type of machine, which may be electrically driven and fitted with caterpillar travelling gear (*Fig. 3*). Such machines may be obtained to dig very high faces, but generally speaking a machine to operate on a vertical face of about 40 ft. and a bucket with a capacity of $3\frac{1}{2}$ yds. loose, or a little over three tons weight, are most useful. The capacity of such a machine, which is operated by one man, is very large if it is kept in continuous operation, but in average working, owing to shunting of trucks, moving rails as the digging proceeds, etc., the normal rate is considerably below the best

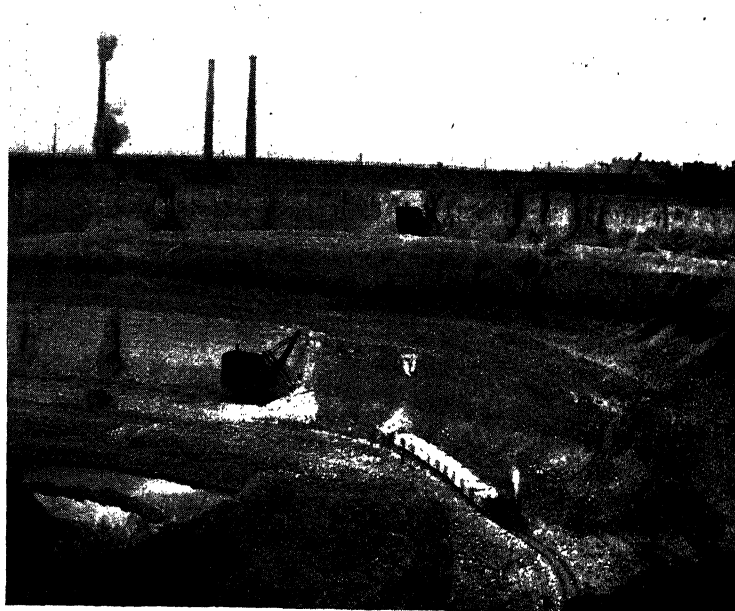


Fig. 3.—Excavating Chalk.

possible output. While such a machine may maintain a digging rate of, say, 120 tons per hour, it will only be digging for perhaps 50 per cent. or 60 per cent. of the time.

With high faces it is necessary to make approach roads at different levels, or to use a second machine working on benchings to dig material and drop it to the bottom level where it can be picked up by the machine working on the bottom level (*Fig. 4*). This involves greater capital expenditure for machines, and also entails handling a proportion of the material twice, but it saves the cost of approach roads, tunnels, etc., and thus there may be little or no difference in the total capital outlay. The machine on the higher level will not be delayed by tipping into trucks, waiting for shunting, etc.; it can operate at maximum efficiency, and will, generally speaking, dig at double the rate of the one on the bottom level.

Another method of dealing with such a situation is to drill the face of the material for a considerable length, and put in a charge of blasting powder suitable to the material being worked. This will cause the face of the material to collapse, so that



Fig. 4.—Digging Chalk in Two Benches by Steam Navy.

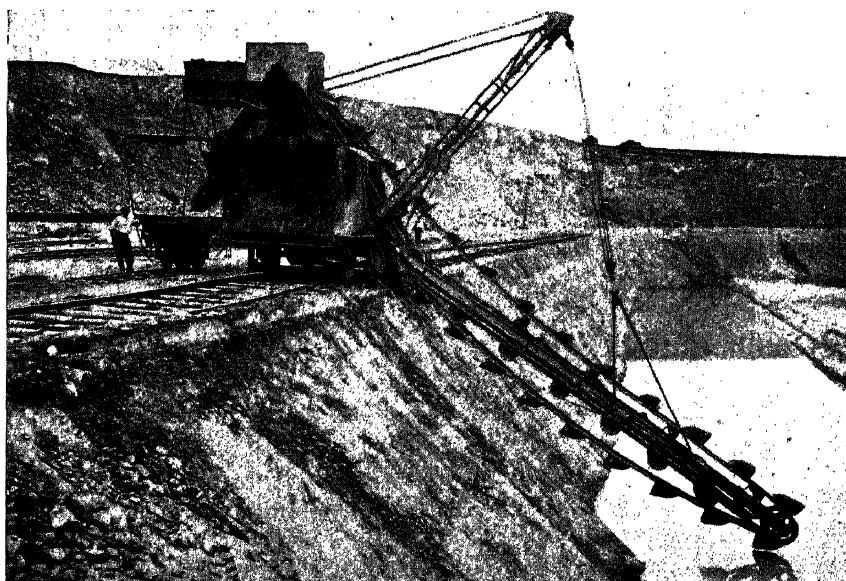


Fig. 5.—Chain Bucket Excavator.

one machine at the bottom can then handle it. A similar result may be obtained, perhaps more safely, by drilling vertical holes along a reasonable length of face from the top of the quarry down to the level of the quarry bottom. These holes are located at suitable distances both from one another and from the existing face, and are formed by compressed-air drills. The holes are charged with powder and the whole simultaneously fired. The capital outlay is relatively low, but the actual cost of winning the materials is rather higher than benching. Generally speaking, however, the higher the face the more effective is this method.

A machine with possibilities for soft materials is a continuous-bucket scraper (*Fig. 5*), in which open-ended buckets of about 1 cu. ft. capacity are mounted at intervals on a very strong chain. This chain runs over drums at each end of a long

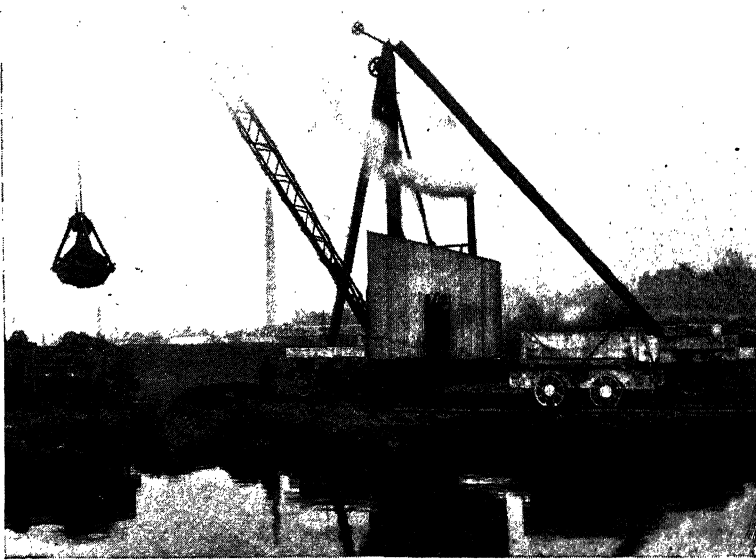


Fig. 6.—Digging Clay in Marsh Land.

lattice-work arm supported by ropes from a heavy carriage running on rails, which houses the driving mechanism, generally electrical, which very slowly moves the whole apparatus along the face of the material. By rotation of the top drum, the chain with the buckets is moved over the face of the material to be removed. The angle of the bucket arm is adjustable so that the slope of the face of the materials may be relatively flat in material which tends to slip. These machines can only deal with soft material free from stones and flints, such as a man could dig with a shovel, as the material as won is actually in the form of laminated pieces about 1 in. thick. Such machines are able to work at a level either above or below themselves, and may be constructed to deal with soft material at the rate of 120 tons per hour from a face 60 ft. above and 60 ft. below the level on which they stand. Thus the total

face dealt with from one level may be as much as 120 ft. They are more expensive in operation than an electric shovel, and a fair amount of labour is necessary for the frequent lateral shifting of the rails upon which the machines and the truck travel, as they can only operate on a face of about 9 ft. without moving, whereas the electric shovel can operate on 40 ft. width of face without moving laterally. An important point is that this machine will operate with the bucket ladder immersed in water, and thus can be used on waterlogged strata without pumping. Such machines are also useful where the level of the top of the deposit is the same as that upon which the works are situated. They operate very well in clay, and particularly if there is sufficient water present to prevent the clay or marl sticking to the buckets; in fact most types of digger operate better with either fairly dry or really wet materials.

Another form of machine which is useful in certain cases is a drag-line excavator. This will, however, only dig moderately soft material from the solid, but it will cover

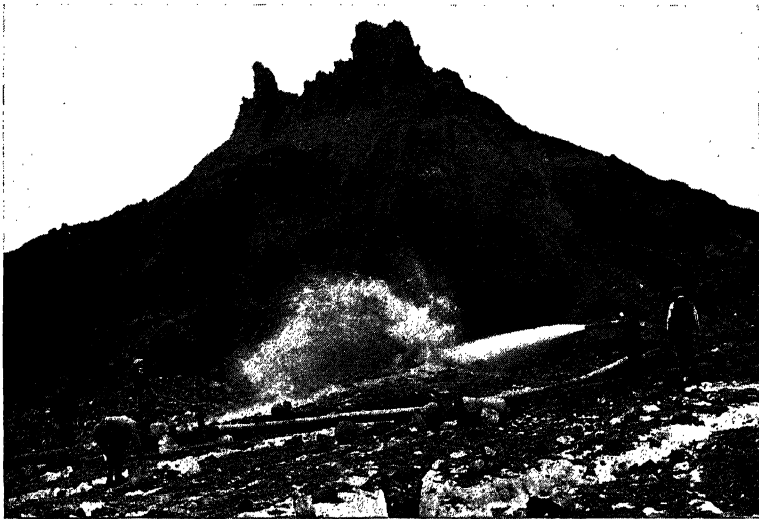


Fig. 7.—Excavating by Water Jet.

considerable areas and will dig below its own level. In suitable conditions the cost of operating is approximately the same as for the electric shovel.

In dealing with very soft clays from river beds or marshes an ordinary crane with grab is very suitable (*Fig. 6*). It is relatively cheap in capital and repairs; it is operated by one man, and a relatively small machine will dig up to 80 tons per hour. In cases where the material is under water the crane is generally mounted on a floating pontoon, and in some cement works where the wet process is used, and the works are adjacent, the wash-mill is mounted on the same pontoon and the clay, in the form of slurry, pumped to the shore.

In almost all cases quarries are open-worked and mining is seldom adopted as it is much more expensive; but mining is necessary in some cases where the deposit is well below the surface and the stratum is of small thickness.

In the case of limestone and hard materials generally the methods mentioned for winning chalk by electric caterpillar shovels and blasting are used.

Transport of Raw Materials

The method of transporting raw materials to the works also depends on topographical conditions. A wire ropeway is most useful and convenient where the level of the ground between the deposit and the works is variable, or where water has to be crossed, and has the merit that the material can be delivered over the crushing or grinding machines at any desired level. Where the ground is fairly level and there are no very sharp curves, standard-gauge trucks and locomotives (*Fig. 8*) are the cheapest form of transport as large quantities can be moved by this means, but if the removal of rails is of frequent occurrence this is more cheaply



Fig. 8.—Chalk Arriving at Tippler over Washmills.

carried out with narrow-gauge rolling stock; much sharper corners can also be negotiated with the narrow (say, 2-ft.) gauge.

In the wet process of manufacture transport by pumping may be usefully adopted in many cases, as has been mentioned for clay slurries. It is, of course, necessary to have cleaning places at the lowest points in the pipe line. A 6-in. diameter pipe-line will, without an unduly high pressure, transport dry material mixed with the requisite water at the rate of about 80 tons per hour.

Mixing Raw Materials

Having decided on the methods for winning the raw materials and conveying them to the factory, it remains to amalgamate them efficiently and accurately in certain fixed proportions; either, in the wet process, with the addition of water; or in the dry process by the complete drying, fine grinding, and mixing of the raw materials in their dry state—this depending upon the nature of the materials.

The estimation and analysis of raw materials are dealt with in Chapter IV but it cannot be too strongly emphasised that the preliminary mechanical blending

of the raw materials requires the utmost technical skill. The thoroughness of this process primarily determines the quality of the resulting cement, and if the manufacturer is to produce a product of regular and reliable quality the supervision of this branch of the manufacture is of paramount importance.

It is essential that extreme care should be exercised in obtaining the correct proportions of the chalk and clay, or whatever other raw materials may be used in the process, so that the resultant mixture may be relied upon to contain the exact chemical constituents necessary for the manufacture of a thoroughly strong and sound cement ; for if the raw materials are not mixed in this proper proportion little or nothing can be done at the later stages of burning and grinding to correct it, and the result will be an inferior product. A very careful check must be kept on the weights of the raw materials, which are adjusted as necessary to the correct

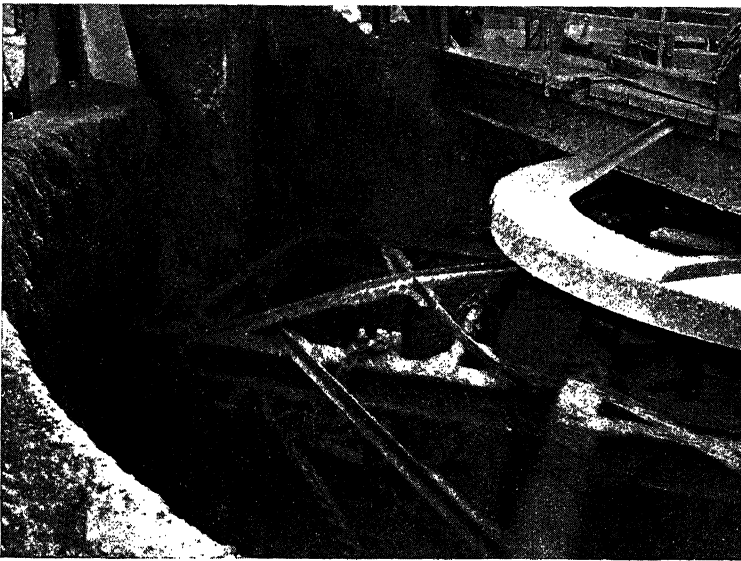


Fig. 9.—“ Roughing ” Mill.

proportions of mixed raw materials ; testing for this purpose by the works chemists should go on day and night so long as manufacture is proceeding. It is obvious that the more regular the composition of the materials the easier it is to maintain the necessary regularity of the mixture, and pure chalk or limestone and good clay are therefore advantageous.

The hardness of the raw materials is of great importance in determining their value, since they must be ground to great fineness before mixing. Pure hard limestones require pulverising to an impalpable flour, almost all passing a 170-mesh sieve, and are therefore costly to treat ; whereas other limestones or chalk-marl containing a considerable proportion of clay are generally much softer, and, the mixing being already done in part by Nature, a better burning combination and finished cement often result without the high cost of extremely fine grinding and consequent high capital outlay.

WET PROCESS.—Of the two principal methods of reducing and mixing raw materials, the wet process is applicable mainly, although not solely, to soft materials,

which generally contain a fairly high percentage of natural moisture. The correct quantities of the raw ingredients are ground and mixed with a considerable amount of water, and produce in the final stage a thick creamy liquid containing from 32 per cent. to 42 per cent. of water, the amount of necessary water varying with the nature of the materials. This method of mixing, as originated and developed in the United Kingdom, is employed by the manufacturers of cement on the Thames and Medway. A further reason for the adoption of the wet process in this case is that the chalk in this area contains a large proportion of flint stones which do not break readily and are very easily separated at this stage as the chalk mixes with the water and the flints can be easily removed.

The soft chalk and clay are weighed into a "roughing washmill" (*Fig. 9*) where water is added in considerable quantities. Generally a brick-lined circular

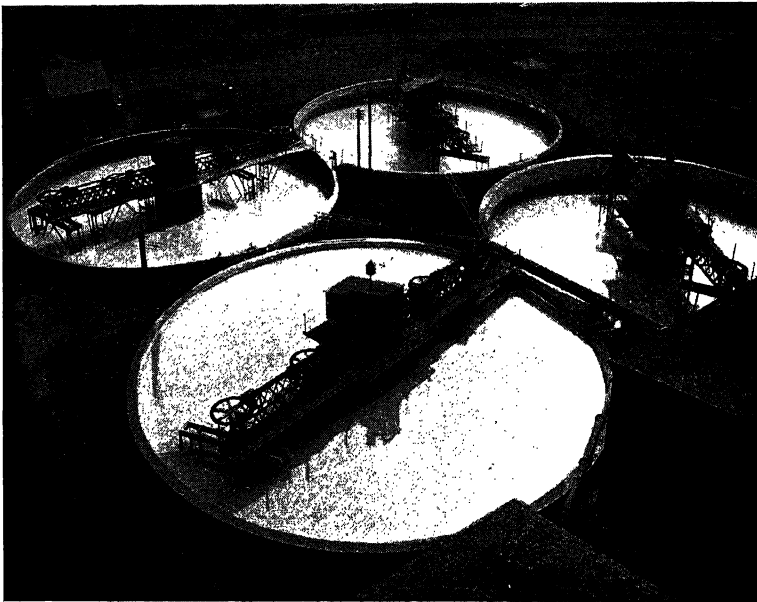


Fig. 10.—Slurry Mixers.

pit is used for the washmill, and this is often 24 ft. in diameter by 5 ft. deep. Approximately half the circumference of this basin consists of vertical gratings through which the material under treatment escapes when sufficiently fine to do so. In the centre is a concrete or brick pier, on which is a vertical shaft rotated through a crown-wheel and pinion and carrying a circular framework from which are suspended harrows fitted with steel tines. The lumps of chalk and clay suspended in water are broken up by the rotating harrows, and the mixture is converted into a thick liquid of creamy consistency which is stirred until fine enough to pass through the gratings. Any flints or stones present remain in the mill and are removed through the bottom from time to time, the frequency depending on the proportion of such stones in the raw materials. The product of the washmill is termed "slurry."

The further reduction in fineness of the raw materials is effected in screening washmills similar to the preliminary mill but revolving more rapidly and having much finer screens; the holes in the screens are usually 0.5 mm. in diameter. With

some harder materials it is necessary for the slurry to be treated finally in a tube mill (described later) or put through a separating mill.

If the raw materials are very hard the form of mill just described is useless and it is necessary to use crushers, either of the roll or jaw variety depending on the size of the pieces delivered to the mill. These raw materials, reduced to a size of about $1\frac{1}{2}$ in. to 2 in. cube, are then fed with the necessary amount of water into a ball mill (*Fig. 11*), which is a horizontal steel cylinder about 8 ft. diameter and about 8 ft. long lined with hard steel plates and shaped so that the internal circumference of the mill is in the form of a series of about twelve steps, each some 6 in. high. Inside the cylinder are about $2\frac{1}{2}$ tons of balls or other shape of grinding media varying in size from 3 in. to 5 in. diameter. The cylinder revolves at a rate of approxi-

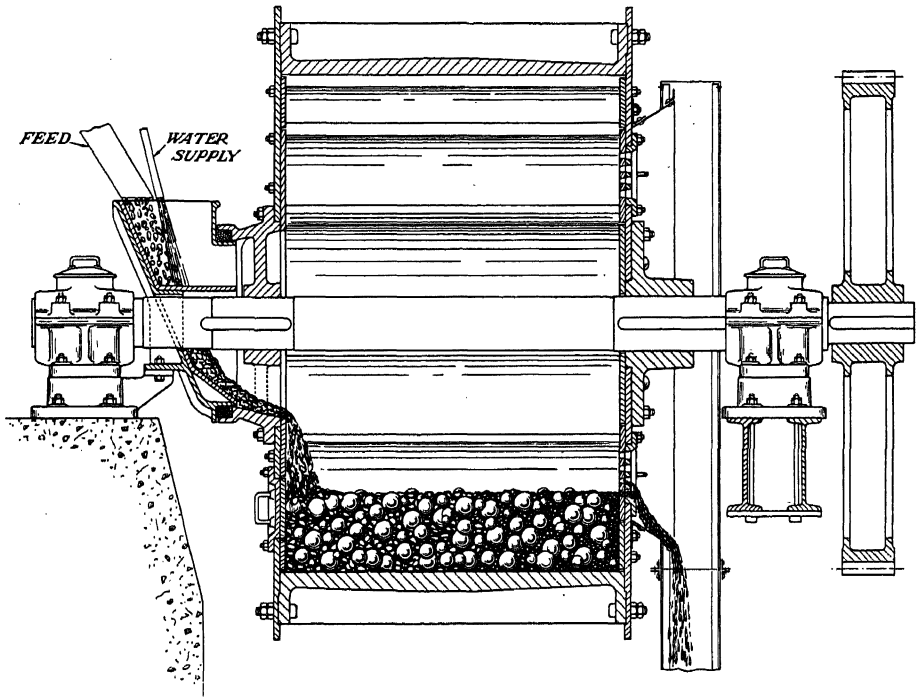


Fig. 11.—Sectional View of Ball Mill.

mately 26 r.p.m., and the balls, in cascading over the steps, reduce the material to a size corresponding to that of the first stage of the process.

After this the material goes to the tube mill for final reduction. This mill is also a horizontal cylinder, but the length is much greater than the diameter; a typical mill for this purpose is 6 ft. diameter by 35 ft. long, and requires approximately 250 h.p. to operate it. In this case the cylinder is lined with plain hard plates, or hard natural silica blocks set in cement. The interior has no steps as in the case of the ball mill. The grinding media consist here of either ordinary flint pebbles or small hard iron pellets or balls of not more than 1 in. diameter, generally somewhat smaller. The mill has usually about one-quarter to one-third of its internal capacity filled with these bodies. The cylinder revolves at about 22 r.p.m. The partially-finished slurry flows in at one end and out at the other,

being reduced to the requisite fineness in its passage, and is then delivered to storage and mixing tanks (*Fig. 10*).

Ball mills and tube mills are now combined in one mill called a "combination" mill. The combination mill has the appearance of a large tube mill, but is divided into two or three compartments, the first having a charge of balls similar in size to the ball mill, the second smaller balls, and the third, which is the longest, the small balls as mentioned for the tube mill. There is no substantial difference in the power taken or the efficiency of grinding of these mills as compared with the ball and tube mills, but the foundation work is simpler.

The fineness of the raw material at this stage has an important bearing on the subsequent quality of the cement. Generally speaking, the nearer the raw material is to the correct composition in its natural state the coarser the grinding can be with satisfactory results. In a good average finished slurry not less than 95 per cent.—better still 97 per cent.—of its solid constituents should pass through a No. 170 sieve.

If the raw materials are hard, relatively dry, and non-absorbent, but of a somewhat variable composition, it is easier to bring them to the correct composition by the wet process than the dry, provided the amount of water is kept so low that the slurry is thick enough to prevent easy settlement of any portion of these materials. This process is called the "thick slurry process" and the moisture in this case may be as low as 30 per cent., although the viscosity and fineness of the slurry may be similar to that of the soft materials with 40 per cent. or more water.

Dry Grinding and Mixing Raw Materials

DRY PROCESS.—In the dry mixing of the raw materials the calcareous and argillaceous materials have to be dried, generally by waste kiln-heat, after passing the preliminary crushing machinery. The dryers were originally kilns built of brick-work, but the dryers in modern plants consist of revolving iron cylinders, or drying drums, about 50 ft. in length and 6 ft. in diameter, supported on steel tyres resting on heavy friction rolls, rotating at about 2 r.p.m. They are usually set with an inclination of about half an inch per foot in the direction of the travel of the raw materials.

The preliminary crusher or rolls reduce the material to $1\frac{1}{2}$ in. to 2 in. cube—the smaller the better; the raw materials are then introduced into the upper end of the dryers, and are caught by cascading channels fitted inside the drums which lift and drop the crushed raw materials as the dryer revolves and present them to the hot gases passing through the drums in the opposite direction to the materials; waste kiln-heat is thus employed for drying purposes.

In cases where vertical kilns are employed in place of rotary kilns, as in some works on the Continent, heating furnaces are sometimes provided for the supply of the necessary heat to the dryers. The size of the dryers depends very largely on the nature of the raw materials.

In dealing with hard crystalline limestone and non-absorbent shale in a dry climate the problem is different from the use of a relatively porous limestone and wet land clay in a rainy country. In any case, however, there is always ample waste heat available to do the work from any dry-process rotary kiln provided a suitable size of dryer drum is provided.

The raw materials after crushing and drying have to be reduced to an extremely fine powder or "flour" (approximately of the fineness mentioned as necessary for

the wet process) by the same type of plant used for grinding clinker. This is also very similar to that described under "Wet Process" for hard raw materials, but without the introduction of water, as will be explained later. They are then carefully and thoroughly mixed to the proper proportions before being conveyed to the kilns for burning.

Having prepared the raw materials either in the form of a fairly thick slurry or a fine dry powder it is necessary to mix them thoroughly so that they shall be completely homogeneous. The method usually adopted in the wet process is to pump the finished slurry from the mills into deep vertical tanks, holding approximately 100 tons, with a conical bottom and a valve. These are set above the main storage tank and fitted with a series of small inlets at the base for the admission of compressed air. When one of these is full the slurry is diverted into an adjacent one, compressed air is automatically admitted, and the whole contents violently agitated. This ensures very thorough mixing in a short space of time—usually about five minutes. The slurry is then discharged into the main storage tanks, which may be open basins of about 70-ft. diameter and 12-ft. deep, holding the equivalent in slurry of some 600 tons of cement and fitted with mechanical agitators, or more frequently to-day a combination of mechanical agitators and low pressure (about 10 lb. per square inch) compressed air. This keeps the contents gently agitated at a nominal cost and prevents any tendency to settlement of the constituent materials.

In some cases the slurry is stored in vertical silos larger but simpler than those mentioned for mixing. These are fitted with compressed-air inlets and the air is admitted at regular intervals. In this case the contents are not discharged into other vessels but remain until required at the kilns. This method is as effective as the former but is rather more costly in capital outlay and operation. It has, however, an advantage in very cold countries as the slurry is not so apt to freeze.

Dry raw material is elevated or pumped by means of a compressed-air and screw-pump to a series of vertical storage tanks similar in many respects to those mentioned for slurry, a useful size for these being about 250 tons of raw material each, equivalent to about 170 tons of cement. Each of these silos is fitted with two or more screw extraction-gears at the bottom and a series of conveyors, generally two under each row of silos. One of these conveyors leads to the main feed to the kilns and the other to the pumps or elevators delivering the ground meal from the mills to the silos. It is then possible to extract the meal from the bottom of one or more of the silos simultaneously into the conveyor leading to the pump and pump it into any other silo, thus circulating the contents of any of the silos until a complete mixture is obtained. It will be obvious that it is more difficult to obtain a thoroughly homogeneous mixture in this manner compared with the wet process and compressed air.

It will also be seen that up to this stage the plant can differ very widely. At the one end of the scale are soft marls of approximately correct composition, easily dug, ground (not necessarily so finely), and mixed in simple mills; at the other end of the scale is hard material requiring extensive drilling and blasting, heavy crushing and milling machinery with dryers to reduce it to a finer state of subdivision, and requiring possibly many times the power required by the soft marl, with correspondingly higher cost of renewals and repairs of the heavy machinery.

The dry process, as has been explained, is employed where the raw materials cannot be satisfactorily reduced by washmills, but is now largely superseded by the wet process. The United States and Canada use the dry process, as do other countries producing cement from hard non-absorbent materials, and where circumstances

allow waste-heat boilers are used for steam raising. The dry method is probably a little cheaper than the wet process on account of the lower fuel consumption in the kilns, but this again depends upon many local factors, and many plants have been changed over to the wet process.

To sum up, the chalk and clay or other materials of similar composition must first be reduced to a very great degree of fineness by the addition of water or by dry grinding. Both these processes break down the cohesion between the particles and leave the material in a very finely divided state ; it is the physical properties of the respective materials to be dealt with which generally determine the method of reduction to be adopted.

Final Composition of Raw Materials

Before the burning process, which is the next stage in manufacture, the prepared raw material mixture is sampled (*Fig. 16*), analysed, and tested to ascertain its composition. The amount of carbonate of calcium (CaCO_3) should be kept within 0.5 per cent. of the quantity found to produce the best cement. The percentage may vary slightly according to the geological formations found in different districts, but a combination of 76 per cent. of chalk or similar calcareous material and 24 per cent. of clay or similar material will, generally speaking, produce a good quality cement. Should the proportion of clay be too high (or the percentage of calcium carbonate fall below, say, 75) the mixture will fuse at a temperature lower than that required for the production of sound clinker, thus rendering it comparatively useless for high-class cement. An excess of chalk (above, say, 78 per cent.) will, on the other hand, allow the mixture to sustain the highest temperature in the kiln without fusion, but the clinker would probably be unsatisfactory due to its unsound or expansive tendencies when ground for cement. A variation of only 0.5 per cent. in the amount of carbonate of calcium will also affect the tensile strength of cement ; other things being equal, high lime content increases the strength and low lime content reduces strength.

Analyses of Mixed Raw Materials

The analyses of mixed raw materials prepared in the ordinary course of manufacture may therefore be as follows :

Silica	14.7 per cent.	} Clay.
Alumina	4.2 „	
Oxide of iron	1.8 „	
Undetermined	1.8 „	
Calcium carbonate	77.0 „	} Chalk
Magnesium carbonate	0.5 „	

Such a material, if properly treated in the further stages of manufacture, will produce a good commercial cement.

Flotation Process for Sorting Raw Materials

A process of separating undesirable constituents in raw materials by flotation (*Figs. 12-15*) has been developed recently, and is in use in the United States, South Africa, and South America. There is no call for the process in the United Kingdom, where there is an abundance of suitable raw material, and the process is only useful in countries where satisfactory raw materials are scarce and it is necessary to use materials which, due to the presence of undesirable minerals and chemicals, are

unsuitable without removing these elements. The process involves a combination of grinding, classification, flotation, and thickening adapted to the specific requirements of cement and the characteristics of raw materials. The purpose is to correct the proportions of the mineral sources of the four oxides essential for Portland cement and, when they are present, to remove proportions of harmful or useless impurities. The process was invented by Mr. Charles H. Breerwood and first applied to a plant of the Valley Forge Cement Company in the United States, to which the following notes, by Mr. G. K. Engelhart, refer.

The typical frothers—mixtures of monohydric alcohols, dilute resinates, and cresylic acid—are satisfactory, and are introduced at various points in the circuit to maintain the desired froth balance. A total of 0.04 lb. of alcohol frother per ton

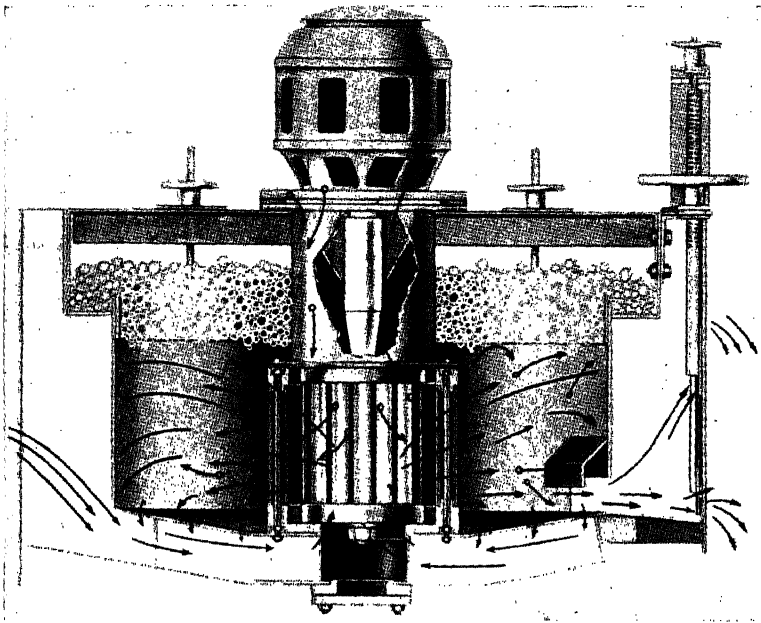


Fig. 12.—Flow Diagram of a Flotation Machine (Cell).

[The flow of the mineral pulp is indicated by plain arrows. The flow of air induced by the rotor is shown by arrows terminating in circles.]

of rock, suspended in about 4 tons of water, is sufficient for the entire circuit. The major portion of the water of the pulp is returned to the flotation circuit.

The usual collecting reagents or promoters for oxide ore minerals are oleic acid, fish oil fatty acids and their emulsions and soaps, and refined talloel. Talloel soap and emulsions are effective collectors of calcite. Some soaps which are useful for certain argillaceous limestone pulps have definite frothing characteristics; these collectors are usually saponified fatty and resin acids, at least one of which requires no separate frother under appropriate conditions. In general, the emulsions are more satisfactory than the soaps in the flotation of calcite, the common mineral form of calcium carbonate, since, in the differential separation of this mineral, soaps sometimes create an excessive and comparatively barren froth. Unmodified fatty acids of high titer are generally unsatisfactory for use in the usual argillaceous lime-

stone pulps, in view of the difficulty in feeding them in small increments to each cell of a stage-oiling circuit and dispersing them rapidly throughout the flotation pulp.

The concentration of calcite from the siliceous minerals in these finely divided pulps is principally the result of adding the collecting reagent in extremely small quantities to each cell of the circuit. The quantity of collecting reagent used is about 0.5 lb. per ton of feed.

The collectors for the siliceous minerals are those which give in solution the long-chain surface-active group in the positive ion and in which the negative ion is usually a halogen. They modify the surfaces of the siliceous mineral grains with limited filming of the oxides. Suitable reagents in this class, when used in normal

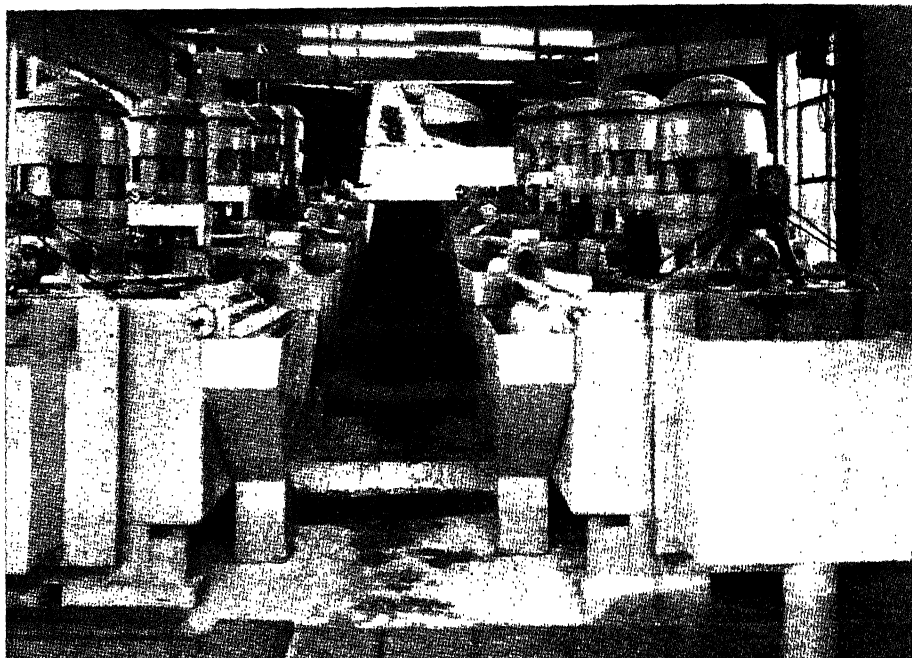


Fig. 13.—Calcite Flotation Circuits.

[The cells of each row are in series. Feeders for stage oiling the reagents are behind the motors. The rake classifier at the rear separates fine mica from the tailings. The mica flotation circuit for the rake underflow is beyond the rake.]

minimum quantities of about 0.4 lb. per ton of feed and sometimes considerably less, will float all or substantially all of the mineral constituents, including acidic, oxide, and sulphide minerals in argillaceous limestone pulps; also, by limiting the quantities and by introducing very small increments at each step in a stage-oiling circuit, differential separations can be made, silicates being readily separated from silica and calcite.

Dispersers are useful in finely-divided argillaceous limestone pulps to reduce natural flocculation and colloidal filming and thereby improve both flotation and classification. In these pulps, calcium lignin sulphonate has been the most effective, either alone or with additions of sodium silicate or soda ash. Depressors are used to decrease floatability of an undesired mineral; e.g. calcium lignin sulphonate,

effective as a disperser, also depresses carbon in various mineral pulps and overcomes its tendency to cause flocculation and to consume disproportionate quantities of fatty acid and cationic reagents.

All known types of Portland cement can be produced solely from the argillaceous limestone quarried on the site, the process making it possible to substitute a small quantity of additional silica for the manufacture of high silica-low alumina cements without extremes in mineral separation. With relation to any modern type of cement, the rock is deficient in calcite and uncombined silica, excessive in total silica and alumina, and satisfactory as to iron. The principal minerals are calcite, quartz, muscovite mica, phlogopite mica, feldspar, limonite, pyrite, pyrrhotite, and dolomite. The removal of a micaceous concentrate is sufficient to correct the deficiency in calcite, to correct the deficiency in uncombined silica, and to permit its substitution in part for special cements, to remove the excess of alumina, to decrease the proportion of magnesia, and to reduce the proportion of alkalis.

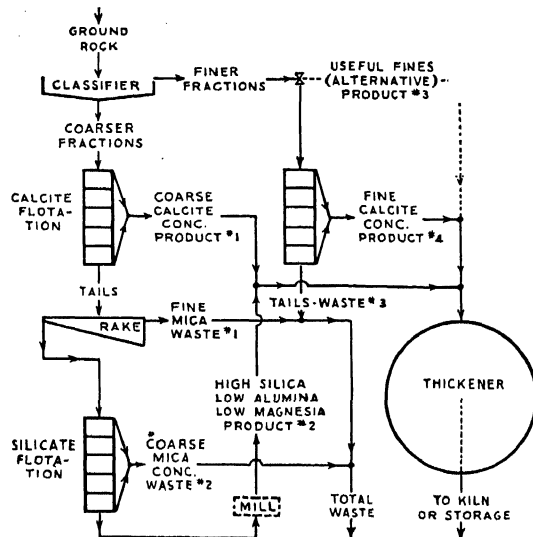


Fig. 14.—Flow Sheet of Minerals Separation Plant.

[Recovered materials are indicated as products 1 to 4. Rejects are indicated as wastes 1 to 3.]

In a circuit found to be most effective (*Fig. 14*) the minerals are ground to about 90 per cent. of -200 -mesh material. The ground materials, at an average rate of 1,300 tons a day, are classified in a hydro-separator, sometimes to provide a controllable proportion of argillaceous materials to form a part of the composition for standard cement, but principally to provide two fractions of limited particle-size ranges to be concentrated in separate flotation circuits. The coarser fractions are subjected to rougher flotation in the presence of a frothing agent and a fatty acid collecting reagent; the concentration is made in a stage-oiling circuit with 0.5 lb. of fatty acid per ton of feed. The tailings of this operation are hydraulically classified to take advantage of the slow sedimentation rate of mica particles to remove the finer suspended micaceous matter as an overflow, which forms the first waste product. The underflow of the tailings classifier is subjected to flotation in a stage-oiling circuit in the presence of 0.5 lb. per ton of feed of a cationic flotation reagent, which concentrates the remainder of the free micas and the pyrite in the froth. This froth

concentrate is the second waste product; the tailings of this operation are the second recovered product of the process, but require further grinding. Part of the first classifier overflow is required as a source of argillaceous minerals and is delivered to the thickener as the third recovered product of the process. The remainder of the finer fraction is subjected to flotation in a rougher circuit in the presence of a fatty acid collector to produce a calcite concentrate which forms the fourth recovered product. The tailings of this operation are highly micaceous and so low in calcite that they are discarded as the third waste product. All the recovered products are continuously delivered to the thickener and recombined to form the ultimate mixture

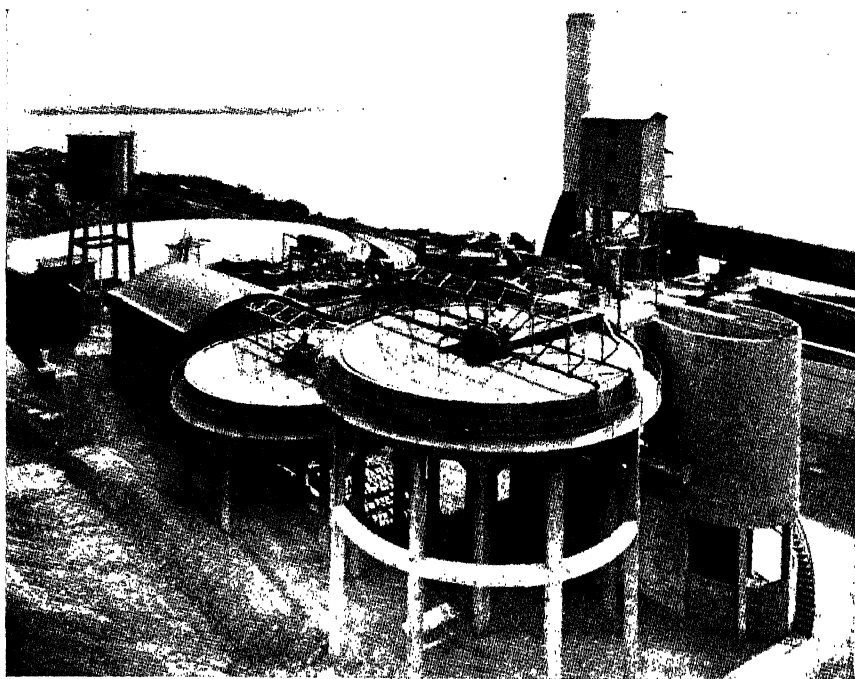


Fig. 15.—Separation Plant.

[Hydro-separators appear in the foreground, the cell house and the thickener in the background, and the kiln at the extreme right.

or the major proportion of a mixture to be completed finally by the addition of a small quantity of silica.

Other accomplishments are the flotation concentrations and recoveries from pulps having a fineness of 100 per cent. of -44μ (325-mesh) and 60 per cent. of -10μ material.

It is stated that the capital cost of installing the process is represented by about the cost of the cell house and its equipment, because the cost of the classifiers and thickener is about offset by equivalent classifier and thickener capacity required for a modern closed-circuit wet-grinding system, and that the cost of the power and the reagents may be recovered by savings in raw grinding, clinker burning, grinding of the finished cement, and in quarrying and handling.

ESTIMATION AND ANALYSIS OF RAW MATERIALS

BEFORE the succeeding stage of manufacture is proceeded with the calcareous and argillaceous ingredients must be mixed so as to give exactly the necessary proportion of calcium carbonate to silica and alumina. It is necessary, therefore, to be chemically accurate in the estimation of the proportions of these constituents contained in the raw materials, and no effort on the part of the manufacturer can bring the resultant cement up to the standard it might otherwise have attained if the proportioning of the ingredients has been inaccurately carried out. The chemist has to exercise a constant check on this part of the process to ensure that the raw material mixture is of normal constitution, and methods must be adopted for accurately testing the mixture, particularly for calcium carbonate, with speed and facility.

It has been explained that the raw material containing lime may be in the form of soft chalk or a hard crystalline limestone, or one of the many grades of calcium carbonate between the two, as well as, in rare cases, slag or alkali waste. Soft white chalks are usually very pure carbonate of lime but contain much water, and hard limestones often contain in a natural state as much as 99 per cent. carbonate of lime.

The clay (containing the silica and alumina) varies almost as much as the lime materials, i.e. from soft river mud to hard shales or slate. The chalk and limestone generally contain few impurities, but the clay may contain magnesia, of which B.S.S. No. 12—1940 limits the amount to 4 per cent., also sulphur and alkalis, which, though not limited by the B.S.S., are not desirable but not harmful if present in small percentages. It is necessary, therefore, first to determine the exact composition of the materials, as some substances are injurious to the finished cement and others simply increase the bulk without any appreciable benefit.

The sampling of raw materials is an important operation calling for great care, and calls for the extraction from a large bulk of material of a small portion which fairly represents the character of the whole. The five principal ways of sampling are: (1) fractional selection, (2) quartering, (3) channelling, (4) split shovelling, (5) riffing. The most common method of sampling is by quartering, and is shown in *Figs. 16, 17, and 18*. In the British Standard Specification for the sampling and analysis of coal the type of riffler shown in *Fig. 19* is illustrated. By whichever means it is carried out, the work should be done thoroughly, as errors incidental to the process of chemical analysis are somewhat insignificant compared with the errors involved in bad sampling. Having obtained the sample it should be ground, passed through the 170-mesh sieve, dried at 105 deg. C., and after further quartering down the quantity required should be bottled ready for use.

Magnesia, nearly always present in the raw material, is generally considered harmful if it amounts to more than 4 per cent. of the finished cement, and is kept within this limit in Great Britain. The effect of excess of magnesia in cement is to cause ultimate expansion due to the formation of magnesium hydroxide from the oxide by the action of water; this is a very slow reaction at ordinary temperatures.

The presence of sulphates in the raw materials is not objectionable. In fact, cement is made at one British works from gypsum in place of the usual calcium carbonate in chalks and limestones. Gypsum has the formula $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. In normal practice part of the sulphates in the raw material is driven off at burning

zone temperature, and the usual sulphate content of clinker is less than 0.5 per cent. SO_3 , and it is not certain in what form the SO_3 is combined, though probably as alkali sulphates.

Gypsum is ground with the clinker to control the setting time. B.S.S. No. 12—1940 limits the SO_3 content to 2.75 per cent., which is equivalent to about 6 per cent.

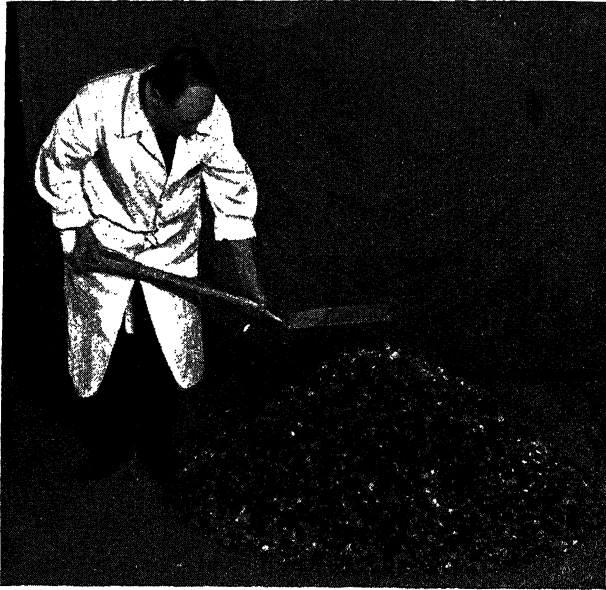


Fig. 16.—Material Piled into Cone.

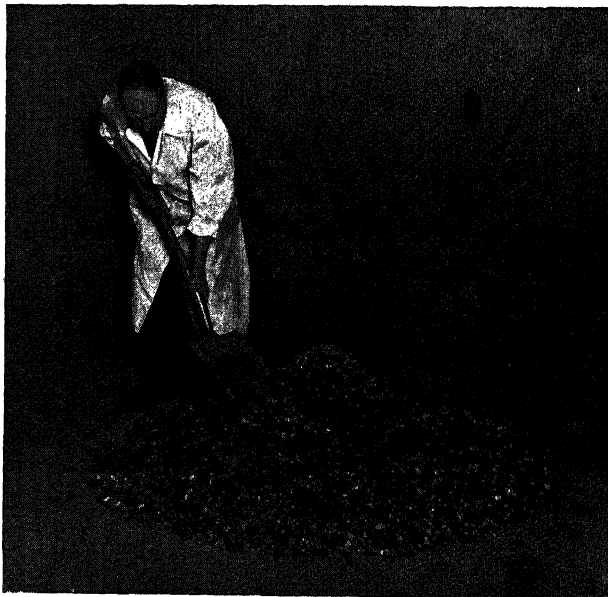


Fig. 17.—Flattening the Cone.

of pure gypsum, less any SO_3 in the clinker itself. The reason for this limitation is that cement mixed with large quantities of gypsum is very unsound due to the formation of calcium sulpho-aluminate.

Alkalis are present in all cements, but in this country seldom exceeding 1.2 per cent. Little is at present known of the effect of alkali in cement.

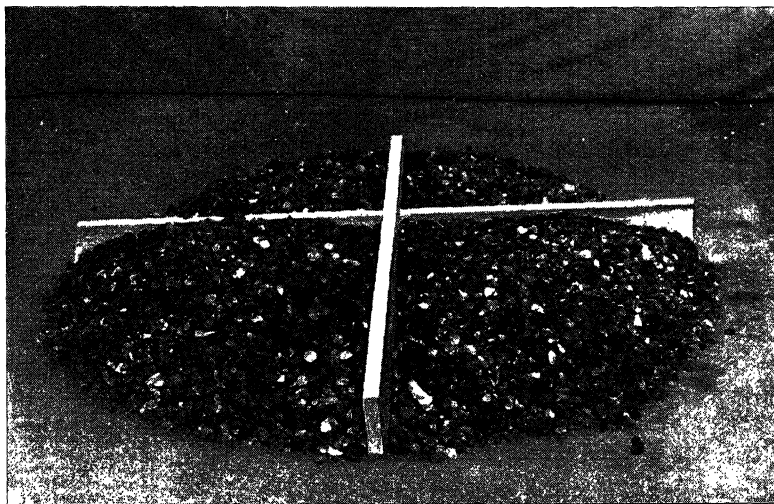


Fig. 18.—Quartering Sample of Raw Material.

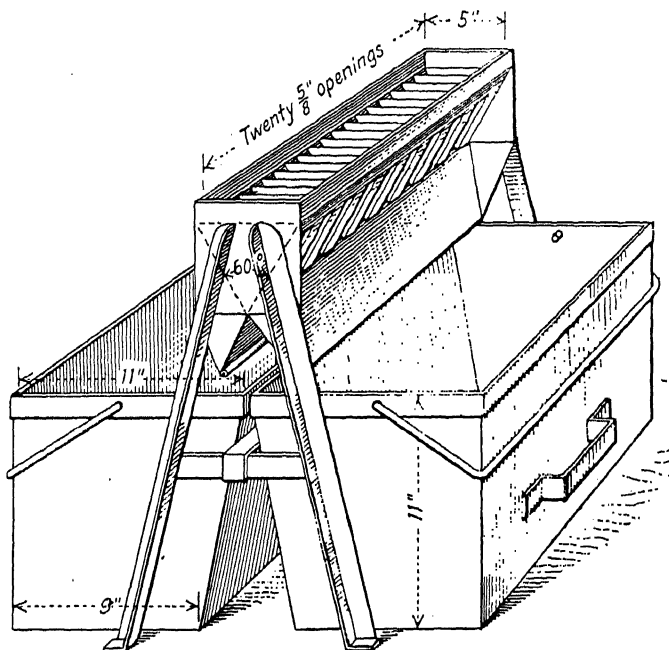


Fig. 19.—Riffler.

Methods of Analysis

The methods usually adopted for analysing the raw materials and the mixture of the raw materials when prepared for manufacture are as follows :

CALCAREOUS MATERIALS, LIMESTONES, ETC.—If there is more than 5 per cent. insoluble silica, etc., it is safer and quicker to analyse by the fusion method, as for clays. If under 5 per cent., proceed as follows :

Weigh 1 gr. of the sample into a porcelain dish ; swill round with water ; add 10 cc. of strong hydrochloric acid ; evaporate to dryness on hot plate, carefully at first to avoid spitting ; then bake for one hour at full heat of plate ; remove, and when dish is cool enough to hold in hand add 20 cc. of strong hydrochloric acid ; leave for 15 minutes, warming very gently if necessary until all red colour of the iron salts has disappeared. Dilute with water, filter, and wash well and dry. Burn off, muffle for one hour, and weigh the silica and insoluble in a platinum crucible to constant weight ; then treat with hydrofluoric acid as follows. Add 20 to 30 cc. of the acid and 1 cc. of strong sulphuric acid and evaporate to dryness over a low flame ; repeat a second time if considered necessary, then heat strongly in the muffle for half an hour and weigh ; repeat until constant. The loss in weight is the true amount of silica ; any residue is extracted by fusion with six or seven times its weight of potassium bisulphate, cooled, dissolved in a small quantity of 10 per cent. hydrochloric acid and added to the main solution which is then made up to 500 cc. and divided into two portions. In one portion ferric oxide and alumina, lime, and magnesia are determined ; in the other ferric oxide.

FERRIC OXIDE AND ALUMINA.—The solution is placed in a porcelain dish, heated to boiling, a few cubic centimetres of bromine water added, then 50 per cent. solution of ammonia added very slowly until solution is neutral, 2 cc. in excess added, and the mixture boiled for two minutes. The precipitate is filtered off, washed twice, and then washed back into the dish, dissolved in a few cubic centimetres of hydrochloric acid and precipitated as before, and filtered, catching the filtrate in the same beaker as the first time. This precipitate should be well washed and then dried, burnt off, and weighed.

FERRIC OXIDE.—The solution is placed in a porcelain dish, treated and precipitated as for the ferric oxide and alumina (only one precipitation being necessary), filtered, and washed. The precipitate is dissolved in hydrochloric acid, heated to boiling, and reduced with stannous chloride. When it is cool 15 cc. of saturated solution of mercuric chloride are added, allowed to stand for 10 to 15 minutes, and titrated with a standard solution of potassium dichromate.

LIME.—To the combined filtrates from double precipitation of the iron and alumina add 30 cc. of 50 per cent. solution of ammonia and bring to boiling ; then add 70 cc. of a saturated solution of ammonium oxalate, boil for five minutes, and allow the precipitate to settle. Decant as much of the clear solution as possible through a filter paper, keeping the precipitate in the beaker. Now dissolve the precipitate in dilute hydrochloric acid and boil, re-precipitate with ammonia and ammonium oxalate, and allow the precipitate to settle. Filter through the same filter paper, allowing the filtrate to mix with the first one. Wash the precipitate with warm water, thoroughly dry, burn off in platinum crucible, ignite gently until all carbon is burned off, then strongly ignite in the blast lamp until the weight is constant. The calcium oxalate is thus reduced to oxide and weighed as such.

MAGNESIA.—The filtrations from the lime are evaporated to small bulk by boiling down in a porcelain dish. When the liquid has been reduced to as small

bulk as possible on the burner it is taken to complete dryness on the hot plate with the addition of 50 cc. of nitric acid to destroy the ammonium salts. When cool, take up with dilute hydrochloric acid, neutralise with ammonia, and filter off any precipitate. An excess of ammonium phosphate solution is added, viz. about 5 cc. of a saturated solution together with 20 cc. of strong ammonia, and the solution stirred briskly for about five minutes and allowed to stand overnight. The precipitate is then filtered off and washed with cold diluted ammonia solution (10 per cent.). The precipitate is then dried, ignited (first gently, afterwards in the muffle), and weighed as magnesium pyro-phosphate.

SULPHURIC ANHYDRIDE.—One gramme of the powdered material is boiled with 50 per cent. hydrochloric acid solution, filtered, and washed. The filtrate is raised to boiling, 10 cc. of a solution of barium chloride are added, and the whole boiled for a few minutes. The precipitate of barium sulphate is allowed to settle overnight, filtered, washed well with warm water, ignited, and weighed.

LOSS ON IGNITION.—One gramme of the powdered material is weighed into a platinum capsule, placed in a cold-muffle furnace (which is lighted and heated gradually to full heat and left for one hour), cooled, and weighed. To correct the loss, for gain or loss of sulphuric anhydride due to treatment in the muffle, the ignited material is transferred to a porcelain dish and boiled with 50 per cent. hydrochloric acid, the insoluble portion filtered off and the sulphuric anhydride determined in the filtrate as before and any necessary correction made to loss on ignition.

TOTAL SULPHUR AND SULPHUR ANHYDRIDE.—One gramme of the material is placed in a porcelain dish, swilled round with water, 2 cc. of pure bromine added, allowed to stand for 5 to 10 minutes, then 20 cc. of 50 per cent. hydrochloric acid added, the whole boiled until all bromine has disappeared. The insoluble matter is then filtered off, the filtrate is raised to boiling, and the barium sulphate precipitated as before. After standing overnight the precipitate is filtered off and treated in the same way as in the sulphuric anhydride determination. Any excess in weight of barium sulphate thus obtained over that from the sulphuric anhydride determination is calculated as sulphur.

ANALYSIS OF ARGILLACEOUS MATERIALS, CLAYS, ETC.—One gramme of the sample, together with 7 gr. of fusion mixture, are weighed into a platinum crucible, heated gently at first over a Bunsen flame, then ignited over a blast lamp to quiet fusion. Allow the crucible to cool below redness, then place upright in cold water to induce rapid cooling so causing the melt to leave the crucible. Now place the crucible in a porcelain dish with 40 cc. of strong hydrochloric acid and 20 to 30 cc. of hot water, and digest until the melt is all dissolved. Take out the crucible and thoroughly wash. Evaporate to dryness on a water bath and when dry leave for one hour on the water bath. Add 50 cc. of strong hydrochloric acid and digest for 15 minutes. Remove from water bath, dilute with hot water and filter off the silica, catching the filtrate in a 500 cc. graduated flask. Wash twice. Transfer the solution back to the dish and take to dryness on the water bath a second time. (While this is being done wash silica thoroughly, catching the washings in the graduated flask.) When dry, leave for one hour, add 50 cc. of strong hydrochloric acid, and take up and filter off any silica as before, catching the filtrate in the same 500 cc. graduated flask, and wash thoroughly.

The two precipitates are then dried, burned off in a platinum crucible gently at first to remove the carbon, then in a muffle furnace for one hour, cooled in a desiccator, and weighed. The precipitate should then be treated with hydrofluoric

acid, any residue from this treatment being fused with potassium bisulphate dissolved with hydrochloric acid and added to the main solution in the 500 cc. flask. This solution is then made up to 500 cc. with cold water and separated into two parts as before. In one portion ferric oxide and alumina, lime, and magnesia are determined ; and in the other ferric oxide.

RAPID DETERMINATION OF LIME.—The following is a useful method for determining lime in cement or in calcareous materials containing less than 5 per cent. of insoluble silica, etc., and is useful as a check on a gravimetric determination. Weigh 0.5 gr. of cement into a 600 cc. beaker, swirl round with water, add 10 cc. HCl, boil until solution is complete, neutralise with 50 per cent. ammonia solution from a burette using a few drops of methyl orange as indicator, add 10 cc. oxalic acid solution (95 gr. per litre), boil, and while boiling add 40 cc. boiling ammonium oxalate solution (50 gr. per litre). The mixture is boiled for five minutes, allowed to settle for ten minutes, filtered, washed thoroughly two or three times by decantation, and (when all precipitate is in filter paper) washed until quite free from excess of ammonium oxalate. Wash precipitate from filter back into beaker, fold up filter paper and lay on the side of beaker. Add 25 cc. of 25 per cent. sulphuric acid, heat to boiling, titrate with potassium permanganate solution (6 gr. per litre), adding filter paper at end, mixing thoroughly into solution to ensure all precipitate is acted upon. At the same time treat in exactly the same way a known weight of pure calcium carbonate (a useful amount to take is 0.55 gr.), then a simple calculation gives the lime content of the cement :

0.55 gr. $\text{CaCO}_3 = 0.308$ gr. CaO .

$$\therefore \text{CaO in cement} = \frac{\text{No. cc. permanganate used for cement} \times 0.308 \times 200}{\text{No. cc. permanganate used for pure } \text{CaCO}_3}.$$

The standard permanganate solution should be kept in a dark-coloured bottle in a dark cupboard when not in use ; it should be made at least a fortnight before use.

CHAPTER V

PROPORTIONING AND PREPARATION OF RAW MATERIALS

THE thoroughness of the mixing and grinding of the raw materials exerts an immense influence on the quality of the cement produced. Cements made from raw materials which have been correctly proportioned and ground to extreme fineness show high strengths, and have quick hardening properties. Constant sampling of the raw meal or slurry (*Fig. 20*) is necessary, and the two methods in general use for keeping

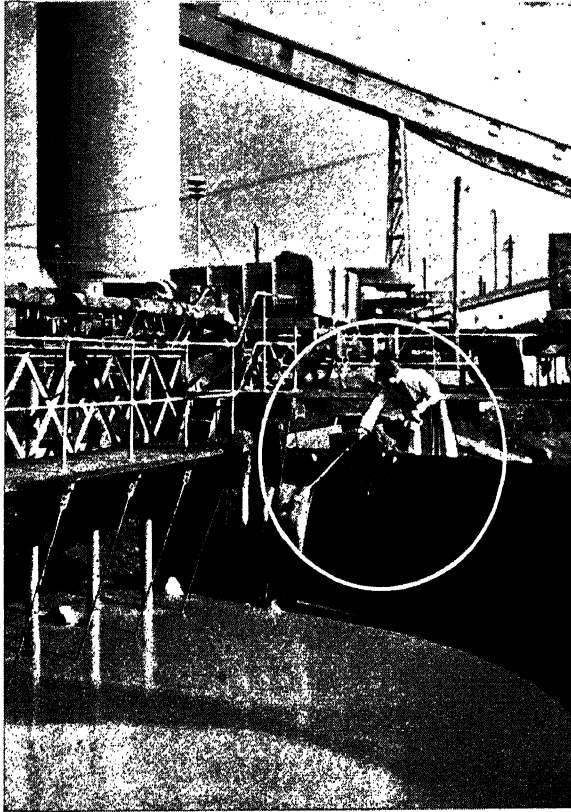


Fig. 20.—Sampling Slurry.

a constant check on the accuracy of the mixing of raw materials are (1) by the calcimeter and (2) by titration.

Calcimeters.

As there are many calcimeters in use a description of two of these instruments will be sufficient, namely, Faija's compensated apparatus, and Scheibler's calcimeter, both used for the volumetric estimation of calcium carbonate by the measurement of carbon dioxide gas evolved. These are illustrated in *Figs. 21* and *22* and act by the direct gas method, in which the carbonate of lime is decomposed by acid

and the evolved carbon dioxide gas collected in a suitable apparatus and measured. The carbon dioxide bears a fixed proportion to the calcium carbonate, and the percentage of lime can be calculated from the volume of gas given off.

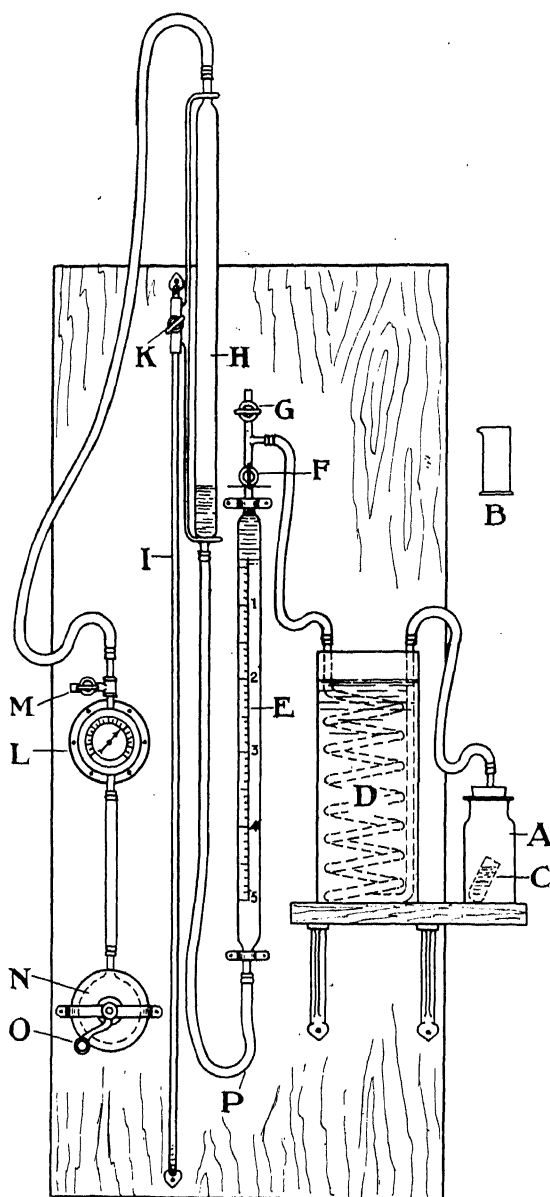


Fig. 21.—Faija's Calcimeter.

FAIJA'S INSTRUMENT.—In the illustration of the Faija instrument (*Fig. 21*) are indicated : A, generating bottle ; B, acid measure ; C, gutta-percha acid tube ; D, condenser with lead coil ; E, gas measuring tube, having at its upper end two taps F and G ; H, equilibrium tube, which may be moved up and down and secured

in any position by fixing it on the rod I by means of the thumb-screw K ; L, barometer to which is attached on its upper side the tap M ; N, india-rubber ball attached by a tube to the barometer ; this ball may be compressed or expanded by turning the handle O, thus adjusting the pressure in the instrument.

The instrument is first secured firmly against a wall, with the tubes E and H perfectly vertical. The india-rubber tube P connects the lower ends of tubes E and H. Tube H is then lowered until its upper neck is a little above the lowest reading on tube E, a funnel is inserted in the neck H, and the tube filled with water

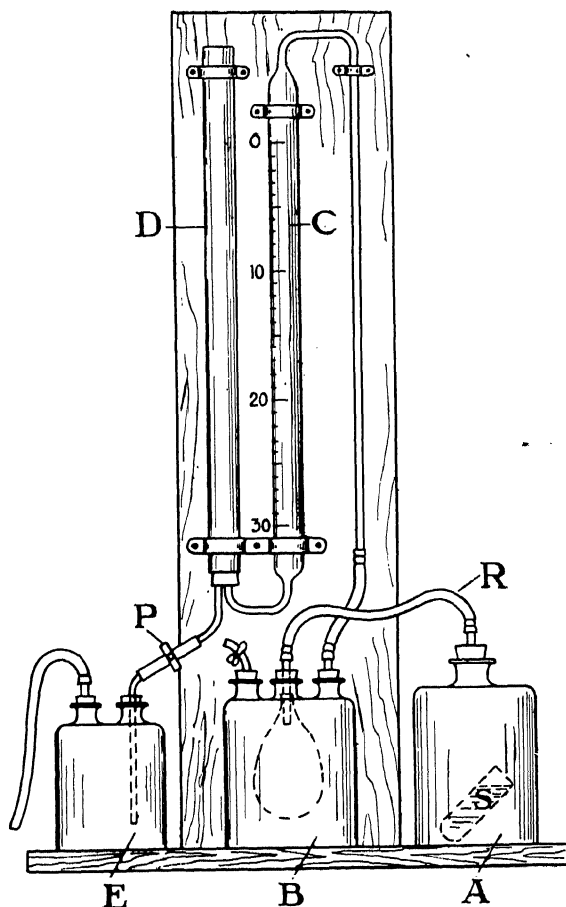


Fig. 22.—Scheibler's Calcimeter.

until the water rises to the lowest reading in tube E. When filling with water the two taps F and G should be open, and tube P pressed to expel any air.

Distilled water is used, and in order that all air may be expelled it should be boiled and allowed to cool before it is poured into the instrument. Then attach the other india-rubber tubes, as shown in the drawing, put the stopper into the generating bottle A, close taps G and M, and see if the instrument is tight. This is ascertained by placing the equilibrium tube H in such a position that there is a difference of several inches in the level of the water in the two tubes E and H and noting the reading of the level of the water in tube E. If the instrument is

tight the water will remain at this level for an indefinite period, but if the water in E rises or falls some of the joints are not tight and they must be made tight by binding them with thin wire. The condenser D should be filled with water.

The mode of working is as follows. First remove the cork from the generating bottle A, take out the acid tube C, then open the taps F, G, and M. Elevate tube H to such a height that the water in tube E is exactly level with the mark immediately under tap F, and secure it there by turning the thumb-screw K. Weigh out the quantity of carbonate of which it is desired to determine the carbon dioxide, and place it in the generating bottle A.

Measure out the proper quantity of acid to use in the measuring glass B and pour it into the acid tube C. Wipe the outside of the acid tube C so as to be sure that no acid has run down the side, and insert it, with a pair of tongs, into the generating bottle A. Re-insert the stopper in the generating bottle A, taking care that it is secure and tight. Close tap G and slack the thumb-screw K, keeping tube H approximately in its elevated position. Now incline the generating bottle A so that the acid runs out of the acid tube C on to the carbonate in the bottle A, and as the gas is generated lower tube H so as to keep the water in tubes E and H approximately at the same level.

Continue shaking the bottle while the gas is generating, and be sure that all the acid has run out of the acid tube C. Place the generating bottle A in the water in the condenser D to cool the gas (which might have been heated by the handling of the generating bottle A) to the temperature of the water in the condenser D. Having left it there for a minute or so, remove it and again shake it, and note if any more gas is generated. When all the gas is generated (which is indicated by the water in tube E remaining in a constant position) close taps F and M, turn the handle O actuating the ball N in either one direction or the other so that the pressure in the barometer is diminished or increased until it indicates the normal pressure of 29.92 in., or 760 mm., which is more distinctly shown by the heavy line. Adjust tube H so that the water in it is exactly level with the water in tube E, and take the reading of the level of the water in tube E. This reading is the amount of gas developed at the standard pressure and simply requires correction for temperature, which may be ascertained by tables already prepared.

When using the instrument the thermometer should be placed in and left in the water in the condensing vessel D, as it is the temperature of this water which governs the temperature of the gas, but it is as well to try to adjust the temperature of the water to approximately the temperature of the atmosphere of the room in which the instrument is worked.

Before commencing an experiment the reading of the barometer should be ascertained, and if above 29.92 in., or 760 mm., the ball N should be deflated so that by turning the handle O and allowing the ball to expand the pressure in the barometer will be decreased. If, on the other hand, the barometer is below 29.92 in., or 760 mm., the ball N should be left fully expanded, when by turning the handle O so as to compress the ball the pressure in the barometer will be increased.

The essential portion of this particular apparatus for the determination of carbon dioxide consists in the addition of a barometer to the equilibrium tube, the pressure in which, and in the gas-generating tube, may be adjusted to a standard pressure. By this arrangement temperature is the only factor which it is necessary to consider when the volume of the gas has been ascertained by the reading of the instrument; and for easy use complete tables have been arranged so that the operation of testing raw materials only occupies a few minutes.

SCHIEBLER'S INSTRUMENT.—Schiebler's calcimeter (*Fig. 22*) consists of the following parts: a small bottle A provided with a perforated stopper in which is placed a tube S of gutta-percha or glass. Another bottle B is provided with three openings in its neck. The central opening of the bottle contains a firmly-fixed glass tube, which connects at one end to A by means of the flexible rubber tube R and at the other (inside the bottle B) with a very light india-rubber bladder.

The left-hand opening is controlled by a pinch-cock on a piece of rubber tubing. The right-hand opening connects B with the measuring tube, which is an accurately-graduated glass cylinder C of 150 cc. capacity. Another glass cylinder D serves to

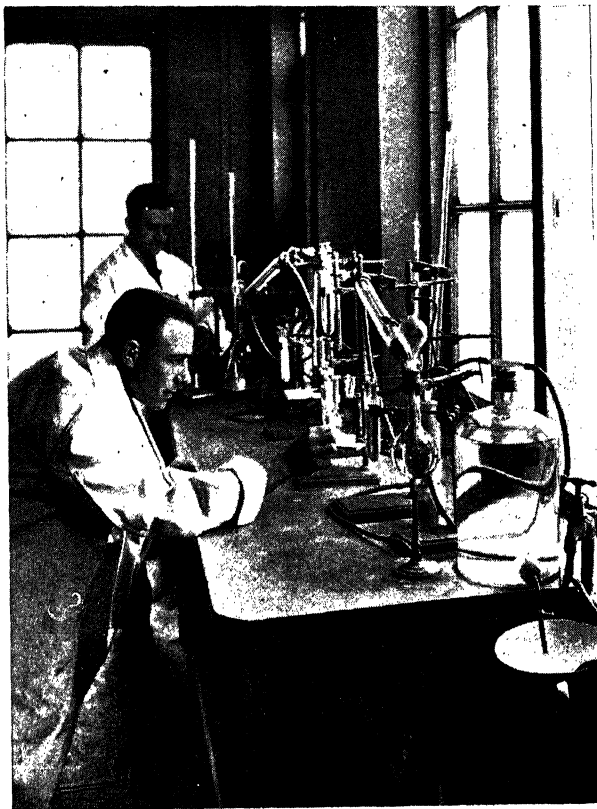


Fig. 23.—A Cement Chemical Laboratory.

regulate the pressure of the gas measured in C; a tube P passes through a stopper into the water reservoir E and is connected with D and controlled by means of a pinch-cock.

A small sample of the raw material, say, 0.5 gr., finely powdered, is placed in the bottle A. The tube or cup is filled with 10 cc. of dilute hydrochloric acid and placed also in the bottle.

Shake the bottle A so that the acid gradually mixes with the sample, and release the cock P in order that the water which has been previously filled into the cylinders D and C may be released as the gas in C displaces the water; keep the water in D on an exact level with C. Then take the reading on C and compare

the volume of gas given off from the sample with the results from testing a standard sample of pure calcium carbonate (Iceland spar).

For example, take 0.5 gr. pure calcium carbonate ; say the gas registers 18 cc. on the cylinder C, and say 0.5 gr. of the mixed raw materials for the manufacture gives 13 cc. of gas. The result is $\frac{100 \times 13}{18} = 72.2$ per cent. of carbonate of lime in the sample.

Other methods can be adopted for estimating the carbonate of lime in raw materials, but those just described are sufficiently accurate for general practical purposes and little or no technical skill is required in their manipulation.

It should perhaps be noted that in the estimation of calcium carbonate, by either of the means here described, the carbon dioxide from any magnesium carbonate present will be measured as from calcium carbonate. The amount of magnesia is usually so small and varies so little, however, that this can in most cases be ignored.

Some instruments are distinguished from the Faija instrument by their greater simplicity, and by the aid of tables provided with them the result can be read directly as a percentage of calcium carbonate. It is only necessary to weigh the quantity of material corresponding to the prevailing barometric pressure and temperature, decompose it with hydrochloric acid, and read on the burette the height of the containing liquid. The number of cubic centimetres so read corresponds to the percentage of calcium carbonate in the substance. The Faija apparatus is, in fact, better adapted for use in many laboratories than some others, because of the calculation which their tables necessitate. An example will explain this, for the purpose of which is given (Table IV) one of the tables for another apparatus ; this shows the weight of material to be taken so that 1 cc. CO₂ represents 1 per cent. CaCO₃ at 700 to 770 mm. barometric pressure, and 10 to 30 deg. C. ; the figures are corrected for the vapour pressure of water.

TABLE IV

Temp. (deg. C.)	758 mm.		760 mm.		762 mm.		764 mm.
15 ..	0.4168 g.	..	0.4179 g.	..	0.4190 g.	..	0.4201 g
16 ..	0.4148	..	0.4159	..	0.4170	..	0.4181
17 ..	0.4128	..	0.4139	..	0.4150	..	0.4161
18 ..	0.4108	..	0.4119	..	0.4130	..	0.4141
19 ..	0.4087	..	0.4098	..	0.4109	..	0.4120
20 ..	0.4067	..	0.4078	..	0.4089	..	0.4100

It will be seen from Table IV that with variations in barometric pressure and atmospheric temperature it becomes necessary to weigh differing quantities of the material for testing. These variations in weight occur in the third and fourth decimal places—in other words, they only amount to about one-thousandth part of a gramme. This may entail additional trouble in the laboratory in very exact weighing, and it is an advantage to take a fixed weight of material. The operator can then keep the weights on the scales unchanged, and successive samples of material may be rapidly weighed without the use of a rider on the balance, thus avoiding calculation and risk of error due to weighing different quantities from time to time. It will be appreciated, therefore, that the use of a constant weight has a good deal to commend it in facilitating rapid and accurate laboratory operation.

An alternative table showing the percentage of CaCO₃ corresponding to 1 cc. CO₂ for a fixed weight of material would therefore appear to be an improvement on

Table IV, and the table has been recalculated so that by taking a constant weight, 0.5 gr., the percentage CaCO_3 content corresponding to 1 cc. CO_2 can be obtained. The method of calculation is as follows :

At, say, 758 mm. pressure and 15 deg. C., taking 0.4168 gr. of material, 1 cc. CO_2 corresponds to 1 per cent. CaCO_3 ; taking 1 gr. of material, 1 cc. CO_2 corresponds to 1×0.4168 per cent. CaCO_3 . (Since by taking a greater weight the quantity of CO_2 corresponding to a definite CaCO_3 content is increased, and the percentage of CaCO_3 represented by 1 cc. CO_2 is diminished.) Taking 0.5 gr. material, 1 cc. CO_2 corresponds to $\frac{1 \times 0.4168}{0.5}$ per cent. CaCO_3 .

Thus we obtain the following table for the percentage of CaCO_3 corresponding to 1 cc. CO_2 , for 0.5 gr. of material, barometric pressures between 700 and 770 mm. and temperatures between 10 and 30 deg. C. after corrections for the pressure of water vapour. Table V enables a fixed quantity of material to be weighed, and removes the difficulty which frequently arises from the varying weights of the first table. It has, however, the disadvantage that the figures given in the table must in all cases be multiplied by the number of cubic centimetres of gas measured.

TABLE V

Temp. deg. C.	758 mm.		760 mm.		762 mm.		764 mm.
15 ..	0.8336	..	0.8358	..	0.8380	..	0.8402
16 ..	0.8296	..	0.8318	..	0.8340	..	0.8362
17 ..	0.8256	..	0.8278	..	0.8300	..	0.8322
18 ..	0.8216	..	0.8238	..	0.8260	..	0.8282
19 ..	0.8174	..	0.8196	..	0.8218	..	0.8240
20 ..	0.8134	..	0.8156	..	0.8178	..	0.8200

Both these difficulties may be avoided by the use of the Faija apparatus. A fixed and easily weighed quantity of material can be taken, and when the determination is complete the percentage CaCO_3 content can be directly read from a prepared table. The CaCO_3 content of the material is $100 x/y$, where y is the number of cubic centimetres of CO_2 evolved from a definite quantity (e.g. 0.5 gr.) of pure calcium carbonate, and x the number of cubic centimetres of CO_2 from the same quantity of the substance under investigation. Corrections must, of course, be made for the different temperatures at which the determination may be carried out. Both these calculations can be completed beforehand and incorporated in a table supplied with the apparatus, which greatly simplifies its use. The characteristics of such tables will be approximately as follows. In Table VI the basic numbers are represented by letters.

TABLE VI

ASSUMING A BAROMETRIC PRESSURE OF 760 MM., A WEIGHT OF 0.5 GR., AND VARIOUS TEMPERATURES.

cc.	15	16	17	18	19	20 deg. C
1 ..	a ..	b ..	c ..	d ..	e ..	f
2 ..	2a ..	2b ..	2c ..	2d ..	2e ..	2f
5 ..	5a ..	5b ..	5c ..	5d ..	5e ..	5f
10 ..	10a ..	10b ..	10c ..	10d ..	10e ..	10f
50 ..	50a ..	50b ..	50c ..	50d ..	50e ..	50f
100 ..	100a ..	100b ..	100c ..	100d ..	100e ..	100f

This survey shows that a table giving the percentage CaCO_3 content at all probable temperatures and for all heights of the containing liquid can readily be constructed, and will not be very extensive. The advantage offered by the Faija apparatus is that it allows the prevailing atmospheric pressure to be ignored.

Titration Test

The "titration" test, or as it is sometimes called the "acid and alkali" method, is perhaps the most accurate of the rapid methods of determining the amount of calcium in slurry. To get the most accurate results, the standard solutions must be standardised on the particular slurry on which they will be used, and not on pure CaCO_3 or Na_2CO_3 .

The calcium in slurry is mostly in the form of carbonate, but there are usually small quantities present as silicate, and there is also a small quantity of magnesium carbonate. The acid will decompose the calcium carbonate and the whole or part of the magnesium carbonate, but may or may not decompose any calcium silicate that may be present. For the particular slurry under consideration all that matters is the amount of calcium present in any form, but the amounts of calcium silicate and magnesium carbonate should not vary much from time to time.

The standard solutions are standardised on the particular slurry, of which the total calcium is known whether it is present as carbonate or silicate, but the amount of magnesium carbonate is not important provided it is constant. The method is to treat the weighed dry slurry with more standard acid than is sufficient to decompose the carbonates, and then titrate back with standard caustic soda solution.

It is convenient to have the strength of the NaOH solution half that of the HCl solution.

PREPARATION OF STANDARD SOLUTIONS.—For use on a works a carboy full of each solution should be prepared at a time.

The alkali solution is made by dissolving 9.9 gr. of pure stick caustic soda per litre of distilled water, and the acid solution by dissolving 45 cc. of concentrated hydrochloric acid per litre of distilled water. These solutions will be somewhat over strength.

Exactly 1 gr. of dried slurry of which the CaCO_3 , calculated from the total CaO , is known, is weighed into a 250-ml. Erlenmeyer flask and 50 ml. of the above acid is added from an automatic pipette. The sides of the flask are washed down and the contents warmed on a hot plate until solution is complete. About 50 ml. of water are added and boiled for 1 to 2 minutes, 6 drops of a 1 per cent. solution of phenolphthalein in industrial spirit are added as indicator and the solution titrated to a distinct pink with the alkali made up as described. Twenty ml. of the HCl solution are put in a 250-ml. Erlenmeyer flask with 100 ml. of water and raised to boiling-point; six drops of phenolphthalein in solution are added, and the solution titrated hot with the alkali solution.

Let x = millilitres of NaOH solution required to neutralise excess acid after solution of carbonate in slurry,

y = millilitres of NaOH solution required to neutralise 20 ml. of HCl solution,

C = per cent. CaCO_3 content of slurry calculated from total CaO in slurry,

V = volume of acid solution made up, and

V' = volume of alkali solution made up,

then the amount of water to be added to the HCl solution is

$$0.95V \left(\frac{0.45 \cdot C}{50 - \frac{20 \cdot x}{y}} - 1 \right) \text{ml.}$$

The above procedure is gone through again and fresh values for x , y , and V obtained. The amount of water to be added is now

$$V \left(\frac{0.45 \times C}{50 - \frac{20 \cdot x}{y}} - 1 \right) \text{ml.}$$

This should bring the acid solution to the standard strength of 1 ml. = 0.0222 gr. CaCO_3 . The procedure is repeated and the value of $\left(50 - \frac{20 \cdot x}{y} \right)$ should be exactly equal to 0.45 · C.

The alkali solution must now be adjusted so that 1 ml. of acid = 2 ml. of alkali. Let x be the last value obtained for the titration of the acid with the alkali, then the amount of water to be added to the alkali solution is

$$0.95V' \left(\frac{40}{x} - 1 \right) \text{ml.}$$

After dilution the titration is repeated and a new value of x obtained. A further quantity of water is added equal to

$$V'' \left(\frac{40}{x} - 1 \right) \text{ml.}$$

This should bring the alkali up to standard strength. This is now checked to see that it is correct.

These solutions are now ready for the determination of CaCO_3 in slurry.

DETERMINATION OF CaCO_3 IN SLURRY.—The procedure is the same as when standardising the HCl solution and the number of millilitres of NaOH solution used to neutralise the excess acid will give the percentage of CaCO_3 in the slurry by reading the appropriate value from the following table.

ml. NaOH	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
10	100.0	99.89	99.77	99.66	99.55	99.44	99.33	99.22	99.11	99.00
11	98.88	98.77	98.66	98.55	98.44	98.33	98.22	98.11	98.00	97.88
12	97.77	97.66	97.55	97.44	97.33	97.22	97.11	97.00	96.88	96.77
13	96.66	96.55	96.44	96.33	96.22	96.11	96.00	95.88	95.77	95.66
14	95.55	95.44	95.33	95.22	95.11	95.00	94.88	94.77	94.66	94.55
15	94.44	94.33	94.22	94.11	94.00	93.88	93.77	93.66	93.55	93.44
16	93.33	93.22	93.11	93.00	92.88	92.77	92.66	92.55	92.44	92.33
17	92.22	92.11	92.00	91.88	91.77	91.66	91.55	91.44	91.33	91.22
18	91.11	91.00	90.88	90.77	90.66	90.55	90.44	90.33	90.22	90.11
19	90.00	89.88	89.77	89.66	89.55	89.44	89.33	89.22	89.11	89.00
20	88.88	88.77	88.66	88.55	88.44	88.33	88.22	88.11	88.00	87.88
21	87.77	87.66	87.55	87.44	87.33	87.22	87.11	87.00	86.88	86.77

ml. NaOH	0	0·1	0·2	0·3	0·4	0·5	0·6	0·7	0·8	0·9
22	86·66	86·55	86·44	86·33	86·22	86·11	86·00	85·88	85·77	85·66
23	85·55	85·44	85·33	85·22	85·11	85·00	84·88	84·77	84·66	84·55
24	84·44	84·33	84·22	84·11	84·00	83·88	83·77	83·66	83·55	83·44
25	83·33	83·22	83·11	83·00	82·88	82·77	82·66	82·55	82·44	82·33
26	82·22	82·11	82·00	81·88	81·77	81·66	81·55	81·44	81·33	81·22
27	81·11	81·00	80·88	80·77	80·66	80·55	80·44	80·33	80·22	80·11
28	80·00	79·88	79·77	79·66	79·55	79·44	79·33	79·22	79·11	79·00
29	78·88	78·77	78·66	78·55	78·44	78·33	78·22	78·11	78·00	77·88
30	77·77	77·66	77·55	77·44	77·33	77·22	77·11	77·00	76·88	76·77
31	76·66	76·55	76·44	76·33	76·22	76·11	76·00	75·88	75·77	75·66
32	75·55	75·44	75·33	75·22	75·11	75·00	74·88	74·77	74·66	74·55
33	74·44	74·33	74·22	74·11	74·00	73·88	73·77	73·66	73·55	73·44
34	73·33	73·22	73·11	73·00	72·88	72·77	72·66	72·55	72·44	72·33
35	72·22	72·11	72·00	71·88	71·77	71·66	71·55	71·44	71·33	71·22
36	71·11	71·00	70·88	70·77	70·66	70·55	70·44	70·33	70·22	70·11
37	70·00	69·88	69·77	69·66	69·55	69·44	69·33	69·22	69·11	69·00
38	68·88	68·77	68·66	68·55	68·44	68·33	68·22	68·11	68·00	67·88
39	67·77	67·66	67·55	67·44	67·33	67·22	67·11	67·00	66·88	66·77
40	66·66	66·55	66·44	66·33	66·22	66·11	66·00	65·88	65·77	65·66
41	65·55	65·44	65·33	65·22	65·11	65·00	64·88	64·77	64·66	64·55
42	64·44	64·33	64·22	64·11	64·00	63·88	63·77	63·66	63·55	63·44
43	63·33	63·22	63·11	63·00	62·88	62·77	62·66	62·55	62·44	62·33
44	62·22	62·11	62·00	61·88	61·77	61·66	61·55	61·44	61·33	61·22
45	61·11	61·00	60·88	60·77	60·66	60·55	60·44	60·33	60·22	60·11
46	60·00	59·88	59·77	59·66	59·55	59·44	59·33	59·22	59·11	59·00
47	58·88	58·77	58·66	58·55	58·44	58·33	58·22	58·11	58·00	57·88
48	57·77	57·66	57·55	57·44	57·33	57·22	57·11	57·00	56·88	56·77
49	56·66	56·55	56·44	56·33	56·22	56·11	56·00	55·88	55·77	55·66
50	55·55	55·44	55·33	55·22	55·11	55·00	54·88	54·77	54·66	54·55

NOTES.—During titration of the excess acid by means of the NaOH solution the end point may be obscured by the presence of clay, etc., which is not soluble. Just before the end point is reached it will be found that the clay will flocculate and settle rapidly leaving a clear solution above. If this is allowed to occur before each addition of acid the colour of the solution may be determined and an exact end point obtained. Results should be reported to the first decimal place only. Arbitrary standard solutions are used intentionally, contrary to the usual practice of using normal solutions or fractional normal solutions. The object of this is to prevent these solutions from being used for determinations other than the particular slurry for which they are prepared. The reason is that, although the standard HCl solution is such that 1 cc. = 0·0222 gr. CaCO_3 in the particular slurry, or $\frac{1}{4·5}$ normal if used for mixtures containing pure CaCO_3 , the solution will not give results corresponding with $\frac{N}{4·5}$. It must be remembered that these solutions are standardised on a particular slurry, in which not all the calcium is present as carbonate, and in which some or all of the magnesium carbonate (MgCO_3) is titrated but not included in the standardisation.

Raw Material Preparation

It has been mentioned earlier that there are two processes for the preparation of the raw materials, namely, the wet and the dry processes. In the former process the materials are broken down and mixed together with the addition of water; in the latter they are roughly crushed, dried if necessary, ground, and mixed in the form of a dry powder.

The opinion is held by some manufacturers that the day of the dry process is passing very rapidly, and plants operating on the process of dry grinding and mixing the raw materials are being converted to the wet process of adding water, on the ground that the better control of the raw mix and resulting higher quality from wet process mixing justify any slight increase in fuel costs. Broadly speaking, the decision as to the adoption of the wet or dry process is an individual problem for each plant, the choice depending very largely upon the character of the raw materials to be dealt with and the price of fuel (i.e. relative economy). A discussion of the economics of the matter may therefore be of advantage.

Certain materials in their natural state obviously lend themselves more readily to one method of preparation than to the other. Chalk or marl, by reason of their softness and normally moist condition, almost compel the use of the wet process, particularly where the chalk contains flints, whereas, other things being equal, hard dry limestones and similar materials appear more suited to the dry process. As has been stated, however, there are advantages to be gained by using the wet process even for hard dry materials, and it is of importance to decide whether these advantages are sufficient to outweigh the disadvantages. Therefore, it may be well to outline some of the considerations affecting a decision in the case of a plant having limestone and shale as its raw materials. It will be understood, of course, that in both alternatives the production of a cement of the highest quality is assumed, and that the ease of mixing the raw materials, which is one of the advantages of the wet process, has to be balanced by suitable methods on the dry process.

At a works where high cost of fuel and shortage of water made the dry process imperative, very elaborate arrangements for mixing and blending the raw materials were installed. As this comprises an attempt to equal the completeness and accuracy of mixing obtained by the wet process, and is claimed to be successful, it may help to an understanding of the problems involved if a description of this plant is included here.

In the quarry there are four ledges of high-lime stone, with ledges of low-lime shales between. Two ledges are quarried for high-lime stone, and on a third the shale is obtained. The quarry equipment consists of two well drills, one steam shovel on caterpillars, and one electrically-driven shovel. The material is loaded into 11-yd. quarry trucks, which are hauled to the crusher by steam locomotives.

The crushing plant is equipped with a roll crusher, 36 in. by 60 in., driven by a 150-h.p. motor. The crushed material is elevated from the crusher to a storage bin by a 42-in. inclined-pan elevator, driven by a 50-h.p. motor. The material is fed from this bin by an apron-feeder to a grinding mill, driven by a 250-h.p. motor; the bin provides a continuous feed to the mill, and stores the heavy intermittent charges of rock delivered to it by the crusher.

The mill product is elevated and conveyed to eight 25-ft. by 65-ft. rock storage bins, from which the mix is made. This product is sampled on its way to storage and passes over an automatic weigher, so that both the quantity and the composition of rock in each storage bin are accurately determined. The mix is then made by

drawing off from the rock storage the proposed mixture of stone by the aid of poidometers and cradle feeders. At least three grades of stone are used, and they are fairly well mixed in the drag and elevator before they enter the dryers. This mix is checked and corrections are made as necessary.

The material in subsequently passing through the dryers and grinding mills is further mixed, although it can, and does, contain a plus or minus error at this point. A pump transport system operated by time-clock distributes the raw material from the mills to four correction silos changing from one to another at frequent intervals. The four correction silos are 25 ft. in diameter and 65 ft. high, with a capacity of 970 tons each, a total of 3,880 tons. Underneath them are four 6-in. pumps operating simultaneously delivering the kiln feed to the kiln-feed bins. The level in these bins is maintained by bin-level signals which operate the valves in the transport line. When the kiln-feed bins are full the valves automatically close, permitting the material to discharge back into the correction silos. This material is then fed to one bin after another in rotation with the mill stream.

It is stated that there is no tendency for the materials to separate or to classify according to weight or fineness during transportation, and that a series of thin layers is built up which will run together during their withdrawal from storage. These thin layers are composed of three constantly-rotating streams, and this constant mixing should level out any errors in the original mix. The possibilities of this system are most interesting to calculate, but it is claimed that in practice in proper operation by this method the kiln-feed error is reduced to a factor comparable with the best possible in the wet process.

A comparison of this elaborate system with that necessary when the wet process is adopted is given in *Figs. 24 and 25* and shows that up to this point the wet process offers advantages in less capital expenditure and ease of control. This will be referred to later when explaining the relative power consumption of the two systems.

Turning now to the comparative economics of the burning operation, it is proposed to compare the alternatives in dealing with limestone containing, say, 95 per cent. of calcium carbonate and with a moisture content of $1\frac{1}{2}$ per cent., and shale or clay containing 10 per cent. of moisture, these figures representing materials very commonly used.

WET PROCESS.—On the wet process it will be assumed (*a*) that the slurry contains 40 per cent. of water, (*b*) that, by efficient drying of the slurry, the gases escaping from the kiln have a temperature of about 450 deg. F., and (*c*) that clinker leaves the cooler at from 200 deg. F. to 300 deg. F. In these circumstances the consumption of standard coal (having 12,600 B.Th.U.'s per lb.) will be in the neighbourhood of 25 per cent. per ton of clinker produced, but such a low chimney temperature presumes the utilisation of the maximum heat contained in the gases for its legitimate purpose in the kiln and leaves no surplus for a waste-heat boiler. Therefore power to run the works must be generated separately or purchased.

The quantity of fuel which will be consumed for power purposes depends upon the efficiency of the works (particularly of the grinding plant), the fineness of grinding, the steam consumption of the prime mover, and so on. A sufficient figure would probably be about 12 per cent. of fuel per ton of cement produced, and for the present purpose that figure will be taken. Thus the total fuel consumption throughout the wet-process works, including burning and power, will amount to about 37 per cent. of standard coal per ton of cement.

DRY PROCESS.—In the dry-process works it will be assumed (*a*) that the raw meal entering the kiln will be damped to the extent of about $7\frac{1}{2}$ per cent. of water,

(b) that the escaping gases will have a temperature of about 1,450 deg. F., and (c) that the clinker leaves the cooler at the same temperature as in the wet process, i.e. between 200 deg. F. and 300 deg. F. The consumption of standard coal per ton of clinker should thus be from 20 to 21 per cent. or, say, 20.5 per cent. A further, say, 1.25 per cent. of fuel for drying the raw materials must be added to obtain the overall fuel consumption, making 21.75 per cent. per ton of clinker for all purposes.

With this coal consumption there will probably be sufficient heat in the escaping gases to generate steam in a waste-heat boiler for the power required to run the plant, and it will be assumed that a waste-heat boiler is attached to the dry kiln. Therefore, theoretically the total fuel consumption for drying the raw materials,

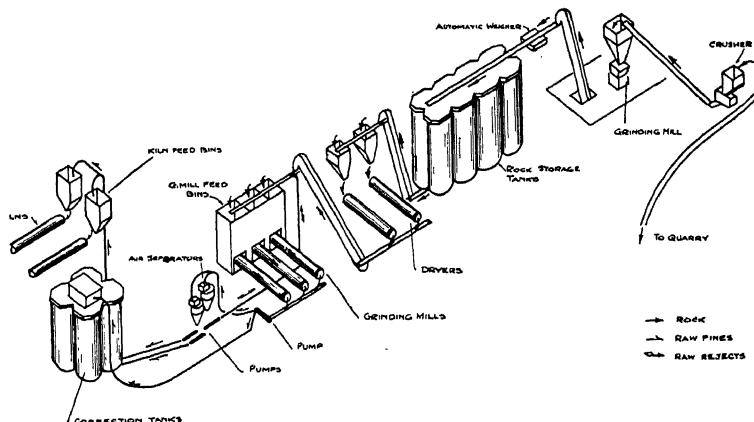


Fig. 24.—Dry Process.

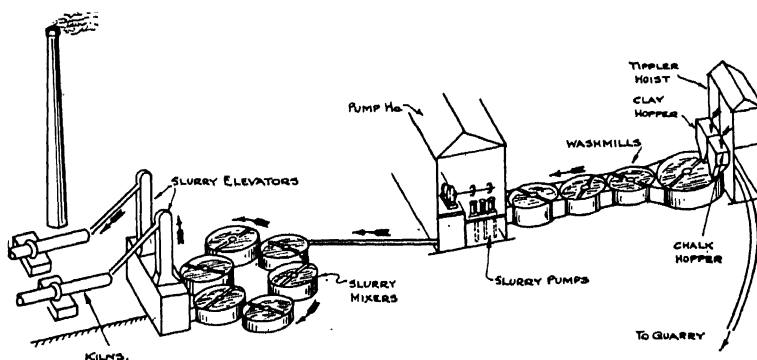


Fig. 25.—Wet Process.

burning, and power purposes would be 21.75 per cent., which is 14.25 per cent. better than the wet-process plant. With coal costing, say, 18s. per ton this represents a saving of 2s. 6 $\frac{3}{4}$ d. per ton of cement. In actual working, however, a certain amount of power fuel would have to be used for starting up and providing for irregularities in running between the kiln and the rest of the plant. If this is assumed to be 1 $\frac{1}{2}$ per cent. per ton of clinker it represents a charge of 3 $\frac{1}{4}$ d. per ton.

Then, again, a waste-heat boiler for a one-kiln plant would probably cost about £3,000 more than a similar one for direct firing, and an allowance of 1 $\frac{1}{4}$ d. per ton must be made for this additional capital charge to provide for interest and depreciation. If allowance is made also for the additional fan-power required, likely to

be about $4\frac{1}{2}$ per cent. of the total power required (or $1\frac{1}{4}d.$ per ton) a reduction of $6d.$ has to be made from the $2s. 6\frac{3}{4}d.$, leaving a net saving of $2s. 0\frac{3}{4}d.$ per ton, or an annual saving of about £8,000 with a plant of a capacity of, say, 1,600 tons per week, subject to any saving in reduced power consumption for wet grinding and any increased cost for extra capital required in dry grinding and mixing plant.

The heat distribution in the two kilns would be approximately as follows :

	WET PROCESS.		DRY PROCESS.	
	Tons of coal per 100 tons of clinker.	Proportion of total coal.	Tons of coal per 100 tons of clinker.	Proportion of total coal.
Reactions	5.6	per cent. 22.4	5.6	per cent. 27.3
Water evaporation, superheating, etc.	10.3	41.2	1.0	4.9
Heat in flue gases from combustion gases and CO_2	4.3	17.2	9.1	44.4
Heat lost in radiation	4.5	18.0	4.5	21.9
Heat lost in clinker and not accounted for	0.3	1.2	0.3	1.5
Total	25.0	100.0	20.5	100.0

This is approximately a distribution which might reasonably be expected in two kilns, one wet and the other dry, using identical limestone and clay and producing the same output of clinker per hour under the assumed conditions already stated.

It will be noted that the distribution of heat differs in the important respect that the heat required for water evaporation and superheating in the wet kiln is much greater, while that available for use in a waste-heat boiler is much less, as the useful heat in the escaping gases is reduced to the economic limit in the wet kiln by efficient operation. In the dry kiln the percentage of heat required for water evaporation is small, and the surplus heat contained in the flue gases is made to do useful work in a waste-heat boiler as an alternative to wasting it. Water evaporation on the dry plant requires about 1 per cent. of coal per ton of clinker, while the heat available in the flue gases is equivalent to about 10 per cent. of coal, against $10\frac{1}{2}$ per cent. and $4\frac{1}{2}$ per cent. respectively in the wet kiln. The amount of heat required for the chemical reactions must be the same in both cases, although the percentage of the total heat used for this purpose is greater in the dry kiln.

The wet kiln is probably as efficient a method of burning as can be expected under present conditions. It has to deal with a large quantity of water contained in the slurry, and the temperatures of both the escaping gases and of the clinker leaving the kiln are low. The efficiency of the dry kiln, however, must be computed after considering the waste-heat boiler and kiln as a single unit. About two-thirds of the heat in the kiln gases can be used to produce steam in the boiler, after allowing for radiation losses in the boiler system and maintenance of the necessary draught, provided proper precautions are taken to prevent infiltration of cold air and so forth. Therefore, in addition to $27\frac{1}{4}$ per cent. of the total coal used for chemical reactions in the kiln, more than 31 per cent. must be added for the work done by the flue gases, making a total of about 60 per cent. for the overall efficiency of the kiln and boiler, against only 25 per cent. for the wet kiln.

In both kilns a certain temperature must be maintained in the firing zone to complete the calcination of the raw materials and to effect clinkering, and therefore

a certain minimum temperature is required in both cases. When the calcination and clinkering are completed the gases retain a similar and considerable quantity of heat. In the wet kiln this heat is utilised to dry out the slurry, while this function is practically unnecessary in the dry kiln and the heat can be used in this case for power purposes.

In considering the problem as a whole, however, we cannot confine ourselves to the limits, however important, of kiln efficiency and coal consumption. It has already been said that in the operations preceding the burning for equal quality the advantage lies with the wet process in several important respects, such as less capital expenditure, ease of grinding and mixing, lower power consumption, freedom from dust, and so on.

Power Requirements

It has sometimes been stated that more power is required for manufacturing purposes on the wet process than on the dry, but experience indicates that the reverse is the case. The wet process appears to be more economical in this respect if the elaborate arrangements which are necessary to secure a thorough mixing of dry materials, and which were described earlier, are adopted; and this is essential if a high quality cement is to be produced. The actual experience in the case of three plants which have been converted from the dry to the wet process may perhaps be quoted.

Plant No. 1.—Using a hard limestone with a small amount of plastic clay mixed in. Consumed 132 kWh. per ton grinding dry to a fineness of 85 per cent. through 100-mesh sieve. Wet process reduced power to 108 to 114 kWh. per ton.

Plant No. 2.—Soft limestone. Power reduced from 129 kWh. on the dry process to 108 kWh. per ton on the wet, with improved fineness.

Plant No. 3.—Using an extremely flinty and hard limestone, consumed on the dry process about 129 kWh. per ton. Now using on the wet process about the same power, but the fineness of the raw material has been increased from 80 per cent. to 92 per cent. through a 100-mesh sieve, with resulting improvement in the quality of the cement. Saving in power was thus used for improved quality.

It is the opinion of some manufacturers who have experience of operating both processes on the same raw materials that the power saving on the wet process is 10 to 20 per cent. over the dry process for an equal quality of cement in both cases. This opinion is more or less confirmed by the experience at some Canadian cement works which have been changed over from the dry to the wet process, the actual power used on the wet process in this case being 14.7 per cent. less than the average power used previously for the same grinding on the dry process. In this case also it is stated that there is considerable saving in the power required for clinker grinding, which is attributed partly to the physical nature of the clinker from the wet kilns. As a partial offset to the saving in power, however, it is stated that the consumption of grinding bodies is much greater in wet grinding than in dry grinding, the increase in the consumption of metal grinding bodies often being more than 100 per cent. on the wet process.

Filters for Drying Slurry

In view of the economy in kiln fuel with the dry process, the use of filters for partially drying the raw materials prepared by the wet process has always appeared attractive. Even if the water in the slurry is as low as 35 per cent. and the moisture

necessarily added to the dry raw material to avoid dust in a dry process kiln is, say, $7\frac{1}{2}$ per cent., the difference represents nearly 0.7 of a ton more water to be evaporated per ton of clinker produced if the wet process of manufacture be adopted. The application of filters has therefore sometimes been adopted in the manufacture of Portland cement with a view to reducing the loss represented by this evaporation. The method involves, however, a good many practical difficulties, which vary with the nature of the raw material used.

The application of the de-watering process is limited, and confined to raw materials particularly suitable to its practical success. It is only possible with continuous and automatic machines, and manufacturers have sought for automatic filters operating under pressure. What is known as "vacuum" filtration is, of course, pressure filtration, although the intensity is limited to the atmospheric pressure. Attempts have been made to obtain higher pressures than are obtainable with

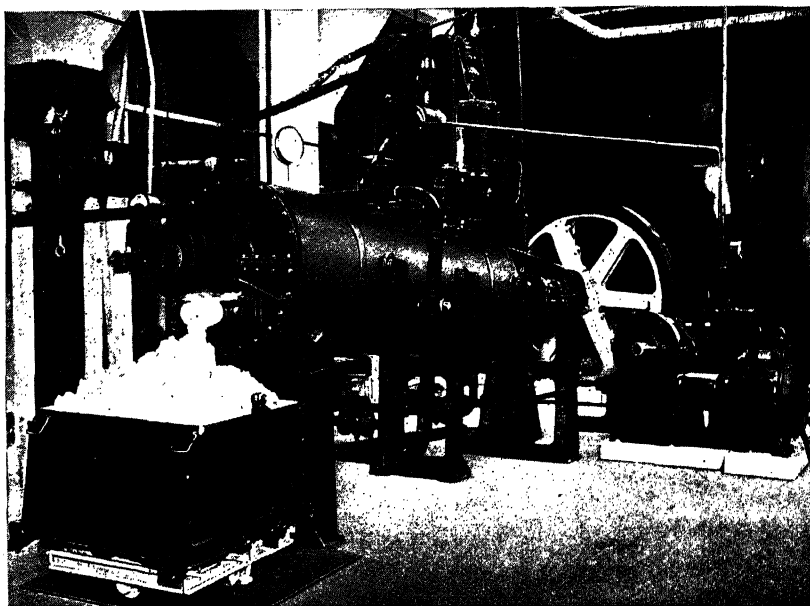


Fig. 26.—Automatic Filter.

vacuum filters, but to date there has not been a simple, accessible, and foolproof unit for continuous filtering under high pressure offered on the market; fortunately, however, cement slurry can be handled at a low pressure. One or two systems are now being developed which may offer possibilities in the future.

The automatic and so-called "continuous" filters (*Fig. 26*) are in reality cyclic machines, each little unit in the machine operating through the successive cycles of filtration, de-watering, and discharging. They are unlike the cream separator, for instance, wherein milk continuously flows from one spout and cream from another. The cyclic functioning of the individual members in the filter, whether of the disk, drum, or other type, is a matter of design so as to proportion the requisite time for filtration, de-watering, and discharge. The essential feature of an automatic filter, however, is its ability to continue filtering at its designed rate for indefinite periods. An apparatus which starts with a capacity of, say, 100, and after the first hour drops

to 95, after the first day to 80, and after a week's operation to 50, is obviously unsuited to feed a rotary kiln, which depends for its efficiency on long continuous runs at uniform output under closely-controlled conditions. The problem must therefore be considered only in relation to the discharge of the de-watered solids at a constant pre-determined rate.

At first sight it would seem that the filter cloth is the principal filtering member, but this is not the case. The filter cloth is the screen which prevents the solids from passing into the drainage member with the liquid, and after the first few grains of solid matter are deposited upon the cloth the filter cake itself becomes the filtering member. As the thickness of this cake deposited upon the cloth increases, naturally the resistance to the flow of liquid also increases. The deposition of filter cake, though variable with different slurries, starts at a relatively high rate and rapidly falls off. Theoretically at least, therefore, the higher the speed of rotation of the automatic rotating filter the greater the capacity per unit area. Practically, however, the speed of rotation is limited by the operation of discharge. Experience shows that it does not pay to operate a filter at a relatively high speed with an indifferent discharge. It is practical only to go at that speed at which all the cake is completely discharged from the filtering cloth; further, the discharge of thin cake is more difficult than the discharge of thick and heavier cake.

The removal of the water from the cake so as to deliver a semi-dry product is a matter of time. The water removed in the first few seconds may be double that removed in the next same number of seconds. There is therefore an economical limit in the time given for de-watering. But another point has also to be considered: thick cake takes longer to de-water than thin cake, so that in practice the amount of water in the semi-dry cake must be balanced with the time required and the thickness of the cake produced. While therefore the ultimate object should be to obtain a cake with the least possible moisture, practical operation demands a degree of "dryness" that will result in a cake which will handle easily and positively into the kiln.

In practice the most important consideration in connection with the de-watering of slurry is its "filterability." This depends entirely on the physical nature of the raw materials. The amounts of argillaceous materials, organic matter, and other substances present in the colloidal state have a direct bearing on the rate of filtration, and determine whether or not the operation will be difficult. Most of the clays used in England are colloidal, or at any rate partially so, and slurry filters have not been adopted in this country up to the present. While, therefore, advance in this direction has not yet resulted in the adoption of the system in England, technical improvements can be visualised which may secure adequate results.

Present-day filters may be classified under two types, namely, the drum and the disk, although it is not unlikely that other and perhaps quite revolutionary types may be developed. In the former the filtering medium forms the surface of a cylinder which is divided internally into sections by longitudinal radial partitions. The spaces formed by these partitions are connected in turn to a vacuum pump and pressure pump; the former draws the water through the filter while the outside surface is in contact with the slurry, and the latter pushes the cake off into a chute or conveyor leading to the kiln.

The disk type consists of a series of thin circular compartments, the filtering surface forming the sides of the disk. This arrangement enables a much greater area of filtering surface to be accommodated in a given space. The action is generally similar to that of the drum type. The whole series of disk-shaped chambers is

supported on a horizontal spindle slowly rotated by means of a worm gear. The shaft, which really takes the form of a tube, provides room for the connections to the vacuum and pressure pumps, and the operation is controlled by a series of valves which are in turn operated by the rotation of the filters. If necessary the process can be assisted by the application of pressure on the slurry side. The operation is as follows: Consider a sector which is just submerging in the slurry contained in the tank. As its upper edge passes below the surface the full vacuum is applied to the sector. As it rotates through the tank a perfectly uniform and homogeneous cake is gradually built up on both surfaces as the filtrate is sucked through the cloth bag. Upon emerging from the opposite side of the tank with the cake fully formed, the corresponding filtrate channel in the centre shaft reaches the wash-water or drying port in the valve plug, to which a vacuum is also applied. This removes a great deal of the liquid or solution entrained in the pores of the cake; the sector next passes into the washing zone. Here the entire cake surface is subjected to a finely-divided spray or wash-water, which is drawn through the cake, thus displacing practically all the liquid or solution still remaining in the interstices of the cake. After passing the washing zone, vacuum is still applied to the sector until it reaches the discharge position, and during this portion of the cycle the moisture is reduced as far as the nature of the cake permits. As rotation continues, low-pressure air is connected. This instantly inflates the filter-bag with air, and as it moves downward between the parallel edges of the cake discharger the cake is entirely removed from the cloth surface and drops vertically through the spaces between the individual pan-compartments on to a belt-conveyor or other device employed for carrying it away.

The de-watering of slurry for the purpose of saving fuel and increasing output with rotary kiln burning on the wet process has not yet been adopted to a large-scale extent, and therefore comments must be reserved for the present upon its utility or practicability or economy, although it is conceivable that in the future this may have a substantial effect in the equipment of cement plants.

CHAPTER VI

PRELIMINARY CRUSHING AND GRINDING

Types of Machines

CRUSHING and grinding are necessary at nearly every stage of the manufacture. The raw material, the fuel for the kiln, the gypsum, and the cement clinker all have to be reduced. Crushing and grinding processes are probably responsible for 80 or 85 per cent. of the total power required for cement works. It is proposed in this chapter to deal mainly with reduction of the raw materials and to discuss coal and clinker grinding later and in their manufacturing sequence.

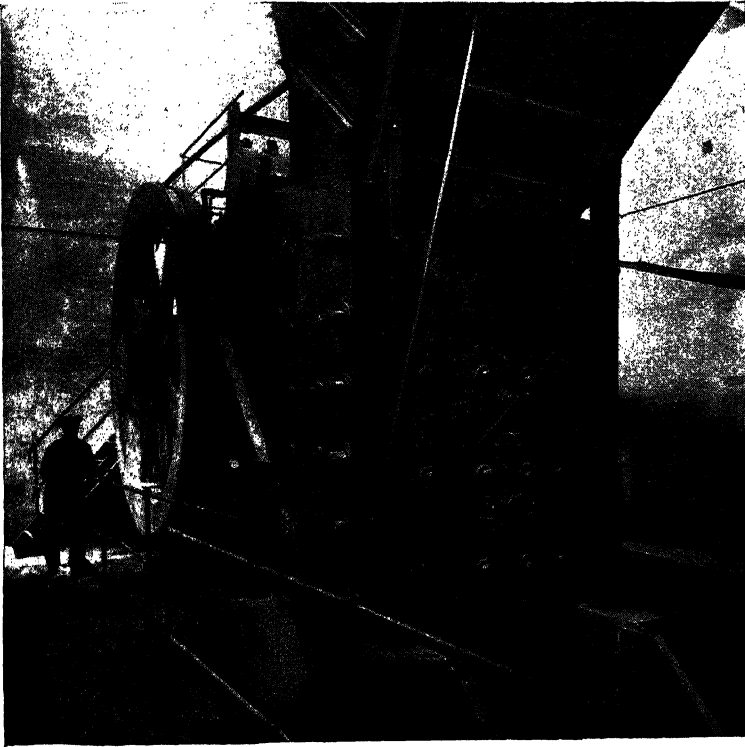


Fig. 27.—72-in. by 48-in. Jaw Crusher.

When the raw materials are soft (white or grey chalk, marl, river or land clay), the power required for grinding or washing is comparatively small, but when they are hard (limestone and shale) it is much higher. White and grey chalks and marl are usually quarried by a power-driven excavator, and the pieces brought to the preparatory plant are much larger than when they were quarried by hand. This, however, is not very important, because the material is "washed" in a washmill, and owing to its soft nature little or no real crushing or grinding is necessary.

Where the raw materials are of a harder variety crushing is necessary, and grinding requires both more power and a longer period for carrying out. In quarry-

ing limestone it is usual to break down large pieces by blasting. When these pieces are handled by power-driven excavators the only limit to their size is the dimension of the excavator bucket, or the size of opening of the crusher mouth. When the pieces are handled manually the limit to size or weight is the workman's lifting capacity ; it is then usual to adopt a limit of 1 cwt. for the larger pieces. When this method is adopted the mouth of the crusher need only be large enough for pieces of this dimension or weight, provided its quantity capacity is sufficient.

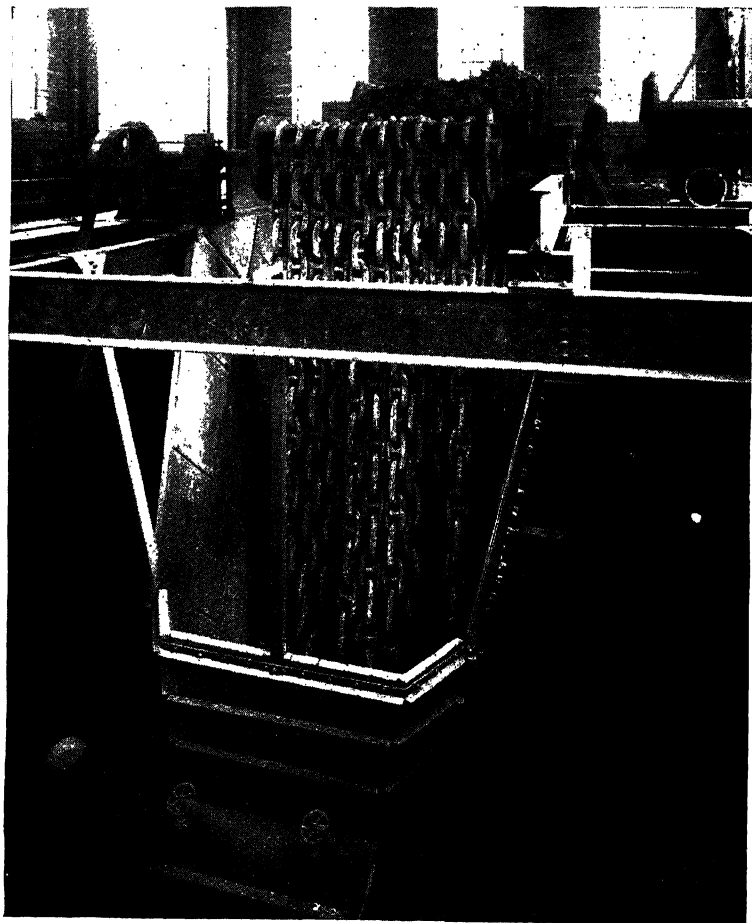


Fig. 28.—Ross Feeder on 72-in. by 48-in. Jaw Crusher.

Crushers are of several kinds ; each has its own characteristic, and is specially suitable for a specific duty. Some machines definitely reduce the whole of the material which passes through them—some produce fines, while others effect no reduction of the under-size. Either jaw or gyratory crushers will operate satisfactorily as breaking-down machines for pieces of material of either of the sizes previously mentioned, but a secondary or finishing machine would be provided for the final preparation for the mill. Any type of crusher will break down more economically than any grinding mill. Experience indicates that the best economic division of duty between the crushers and the grinding mills lies about or between

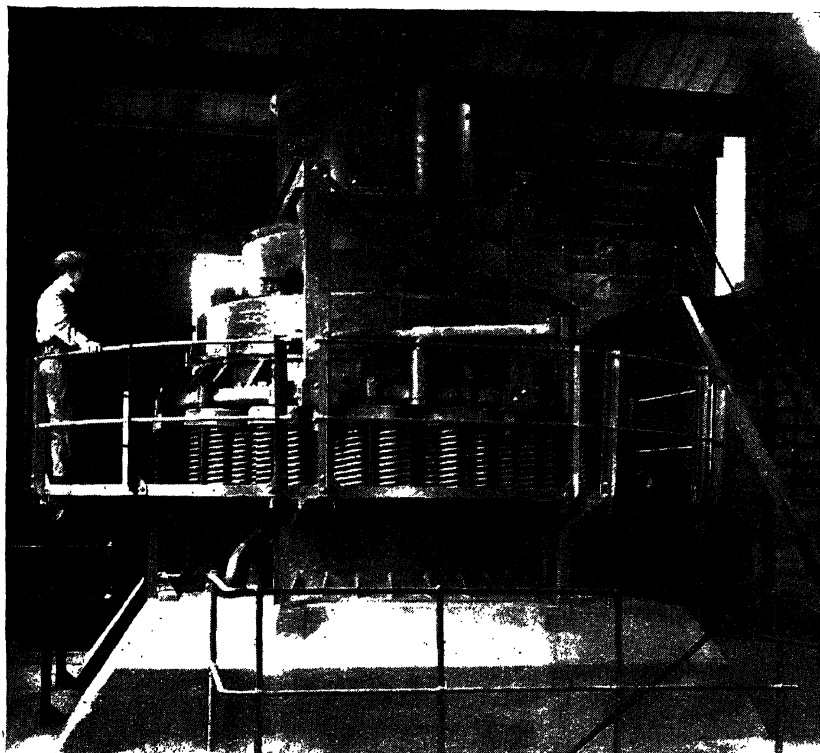


Fig. 29.—Vertical Disk Crusher.

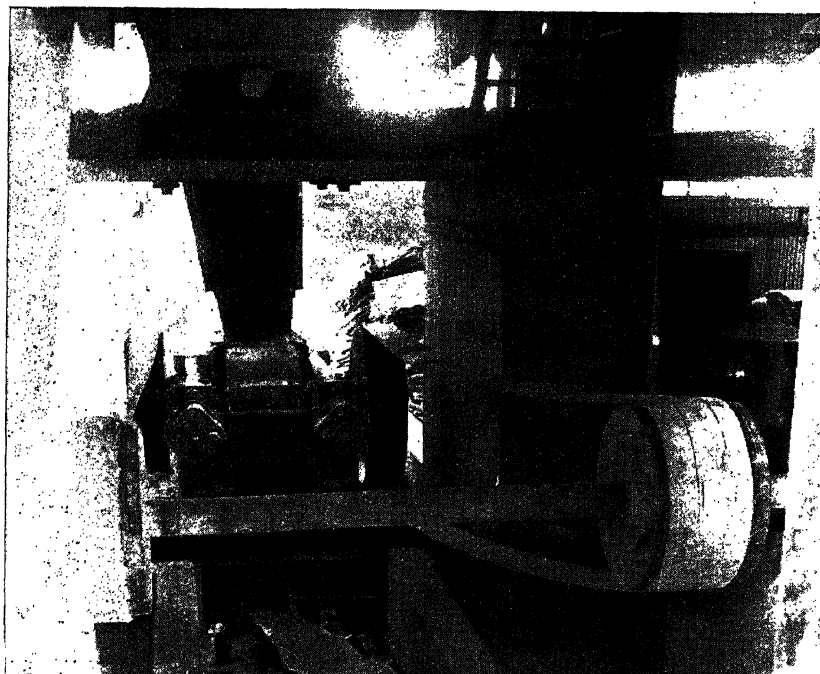


Fig. 30.—Gypsum Crusher.

a ring size of $\frac{3}{4}$ in. to 1 in. Where suitable crushers are available they should prepare the mill feed to this size. The economic reduction ratio of the jaw and gyratory type crushers is about 4 to 1 or $4\frac{1}{2}$ to 1.

With the hammer-type machine there is no reasonable limit to the size of pieces fed into the mouth of the machine up to its capacity, nor to the amount of reduction that can be effected. This type of machine, equipped with a suitable feed, will accept pieces of limestone rock as large as 40 in. by 24 in., 30 in. by 18 in., or 12 in., and will produce from these large pieces of rock a product which will pass a 1-in. ring. A characteristic of the hammer-type crusher is its tendency to produce fines. This makes it particularly suitable for breaking down the raw material for feeding any type of mill.

The power usually taken by any of these machines would amount to, say, 2 b.h.p. per ton for very large reductions and $\frac{3}{4}$ to $1\frac{1}{4}$ b.h.p. per ton for small reductions.

A regular feed is essential for the satisfactory operation of every type of crusher. It is not sufficient to build a large hopper over the crusher mouth and expect it to function satisfactorily, as if the feed is not regular the crusher will be choked or starved. The hopper should be built away from the crusher and a feeder provided. A magnetic separator of some kind should also be installed if " tramp " iron is likely to be met.

Jaw Crushers

This is probably the earliest type of crusher (*Fig. 27*). A swinging jaw (or jaws) operates against a fixed jaw, the movement being produced by an eccentric or crank spindle operating through a toggle joint. The framing of the smaller machine is usually a one-piece iron casting, but the larger machines are usually built of steel castings. The largest machine yet made has a jaw opening of about 8 ft. by 6 ft. The jaw crusher functions for about half its running time. It is very suitable for dealing with hard, dry, crystalline, and non-clogging material, but is not so suitable for gypsum or similar tough material. As previously mentioned, the most efficient reduction ratio is about 4 or $4\frac{1}{2}$ to 1. The pitch of the corrugations in the jaw face and the size of the product required should be correlated. V corrugations and ridges are most suitable for the materials dealt with by this machine.

Gyratory Crushers

Gyratory machines are of more recent introduction. They function for the whole of their running time, but they are larger and more costly, and as breaking-down machines are not generally so suitable as the jaw crusher. The gyratory crusher is, however, more suitable for gypsum. When used for gypsum the crushing surface should be of semi-circular or corrugated section rather than V section. The reduction ratio of this machine is about the same as the jaw crusher, and the product would be similar to that of the jaw machine. The gyratory crusher requires more room vertically than a jaw crusher of similar capacity.

Roll Crushers

There are several types of roll crushers : single roll, double roll, smooth surface, corrugated surface, high-speed roll, slow-speed gear-driven roll, etc.

The single-roll slow-speed gear-driven machine is suitable for breaking down limestone and similar raw materials. Such a machine has been constructed with a

capacity of 350 to 400 tons per hour. The feed may be as big as 3 ft. cube and the product 6 in. cube, or even less. This machine requires 400 to 450 b.h.p. Crushing is effected by the toothed, serrated, or corrugated surface of the slow-speed roll feeding the material against a fixed jaw. The machine is strongly constructed, and its reduction ratio is larger than either of the former machines. The quantity capacity is also large. A sectional illustration is given in *Fig. 31*.

Double-roll machines, operating at high speed, are sometimes used for reducing oversize pieces for mill feed. The whole of the mill feed may be passed through the rollers on its way to the mill, but the oversize pieces only are broken down. An advantage would result if the fines were eliminated, thus preventing undue wear on the surface of the rollers. The reduction ratio of two-roll machines with comparatively smooth surfaces is about 3 to 1; if the surfaces are corrugated the ratio may be larger.

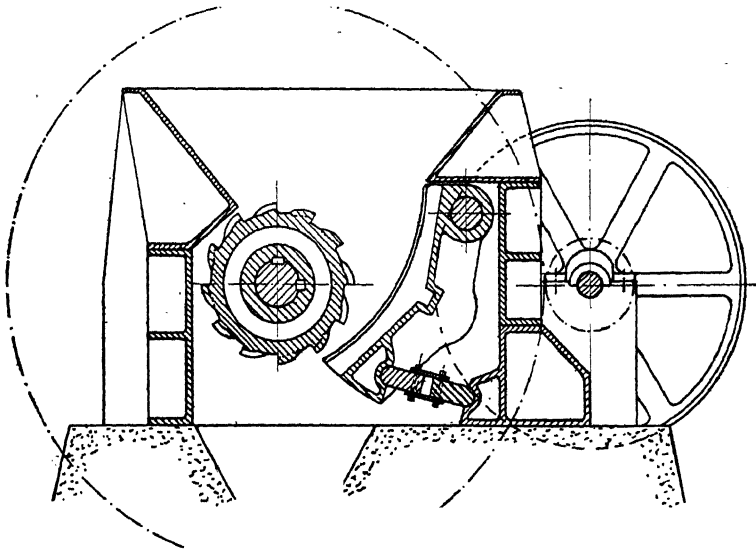


Fig. 31.—Single-roll Crusher.

Double-roll slow-speed crushers have been used for dealing with coal for rotary kilns, with the object of producing a feed suitable for the coal-grinding mills. In *Fig. 32* a machine is shown with three pairs of roll shafts, fitted with tooth-type disks. These disks are narrow, and there are distance-pieces between adjacent disks in the form of a disk of smaller diameter with a finely serrated surface. The teeth in the upper part are coarser and of larger pitch than in the lower. It will be noted that the separate shafts of each of the first two pairs rotate at different speeds; the lower pair rotates at the same speed. As coal is a comparatively non-abrasive material, there is no objection to undersize material passing through the rolls with pieces which require crushing, but probably 15 per cent. of the product would exceed the size which the lower pair of rolls is set to crush. The power required for a unit of this kind would be small, say, $1\frac{1}{4}$ or $1\frac{1}{2}$ b.h.p. per ton, but if the coal were relatively fine, and the lower rolls alone required, the figure obviously would be less. Indeed, the friction absorbed in rotating the rolls would be greater than the power necessary for crushing. A safe figure would be 0.7 to 0.8 b.h.p. per ton crushed.

Hammer-Type Crushers

Hammer type crushers are made with either a single or a double spindle. As mentioned earlier, they will accept as feed whatever size pieces will enter the mouth

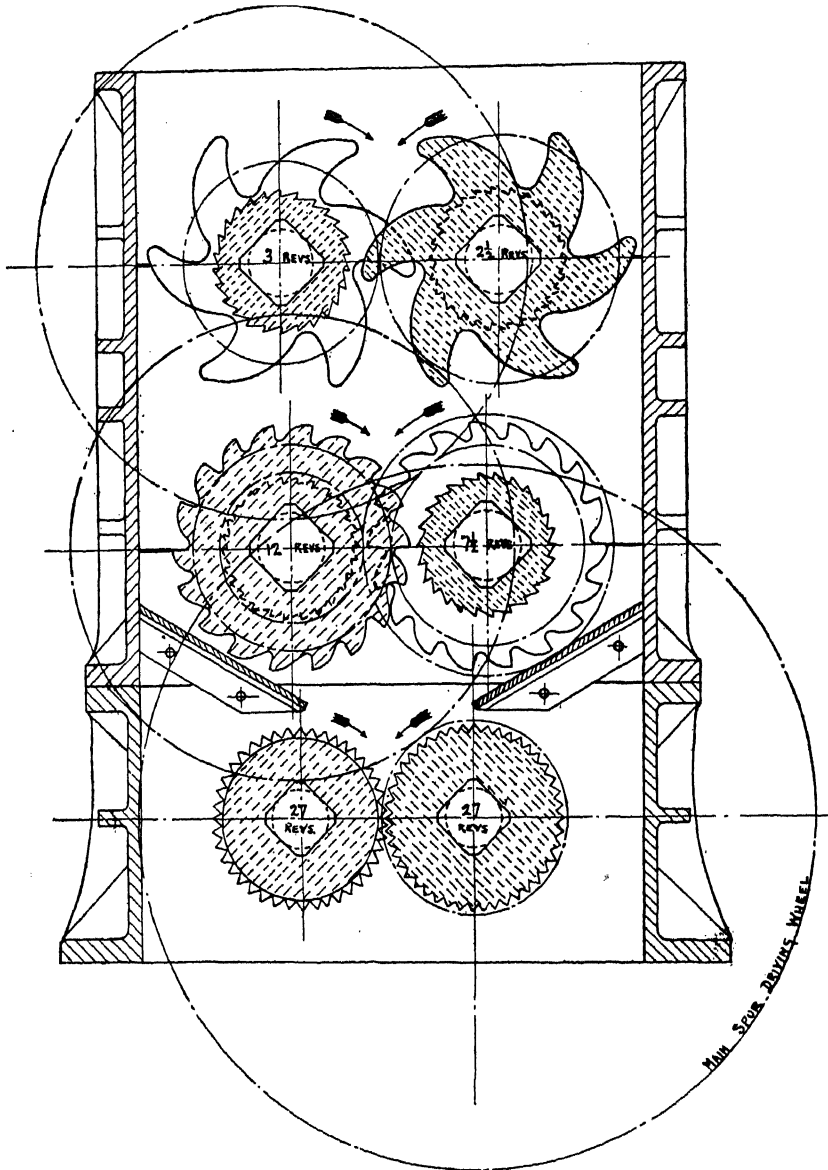


Fig. 32.—Six-roll Coal Crusher.

of the machine, and will discharge a product of predetermined size. The dimensions of the space between the grid bars do not seriously affect the size of the product. As the movement of the hammers is transverse to the length of the grid opening,

the material passed through is consistently smaller than the space. *Fig. 33* shows a section through a double-spindle machine, and the difference in size of the feed and discharge which is characteristic of this machine. The feeder performs an important part in the operation, as this type of crusher would not function satisfactorily without a suitable feeder.

Disk Crushers

The disk crusher is made horizontal or vertical (*Fig. 29*). A section of a horizontal machine is shown in *Fig. 34*. This type functions for the whole of its running time. Its reduction ratio is comparatively small, viz. $3\frac{1}{2}$ or even 3 to 1. It reduces the oversize material to the size predetermined by the initial setting of the machine without further reducing those pieces which are already of that size. Crushing is effected by pressure exerted by two smooth-dished (or concave) surfaces. This pressure is caused by the pendulum-like movement of the end of the spindle, which is caused in turn by the eccentricity of the pulley. The crushing surface is large in both types of machine, and considerable working life is obtained without renewal of wearing parts.

In considering crushers, specific reference has been made to limestone and material of that class; the same remarks are, however, entirely applicable to shales and other material of the kind. It is usual after crushing to elevate or transport the crushed material to hoppers, silos, or stock-bins ready to be transported as feed to the grinding mills.

Grinding Mills

Grinding mills may be of the single-unit or the two-mill type. For many years the two-mill type has had preference, the preliminary mill being fitted with sieves or their equivalent so as to limit the dimensions of the discharge. The discharge from this mill becomes the feed for the finishing mill, which has no sieves at all. In the two-mill unit the residue in the product of the finishing mill is determined by the residue in the preliminary mill product and the grinding capacity of the finishing mill.

During recent years considerable progress has been made with single-unit mills of large dimensions. Mills of 8 ft. diameter by 40 ft. or 45 ft. long have been built and put into service. These machines require a charge load of 50 or 55 tons and a 700 or 800-b.h.p. motor to drive them. When correctly tuned-up, mills of this size will reduce 15 to 20 tons of limestone to slurry per hour. The output, however, depends upon the tuning-up of the mill, the hardness of the stone, and the final residue. The mills are divided into three or four compartments, generally loaded with balls of different sizes, as indicated in *Fig. 35*, but modified in detail to suit wet conditions. Although single-mill units reduce the cost and simplify the arrangement of large installations, it appears difficult to obtain the same output at the same residue for the same power per ton as is obtained from two-unit mills.

Raw material grinding may be carried out wet; that is to say, sufficient water may be fed with the material into the preliminary mill to produce slurry of the correct moisture as it leaves the finishing mill. Raw materials, owing to difference in viscosity, require different percentages of water. A soft chalk and clay mixture, for instance, needs between, say, 40 and 42 per cent.; if the moisture content were much below this figure the liquid would be troublesome to pump and would set up excessive pressure in the pipeline. In the case of slurry made from hard raw materials

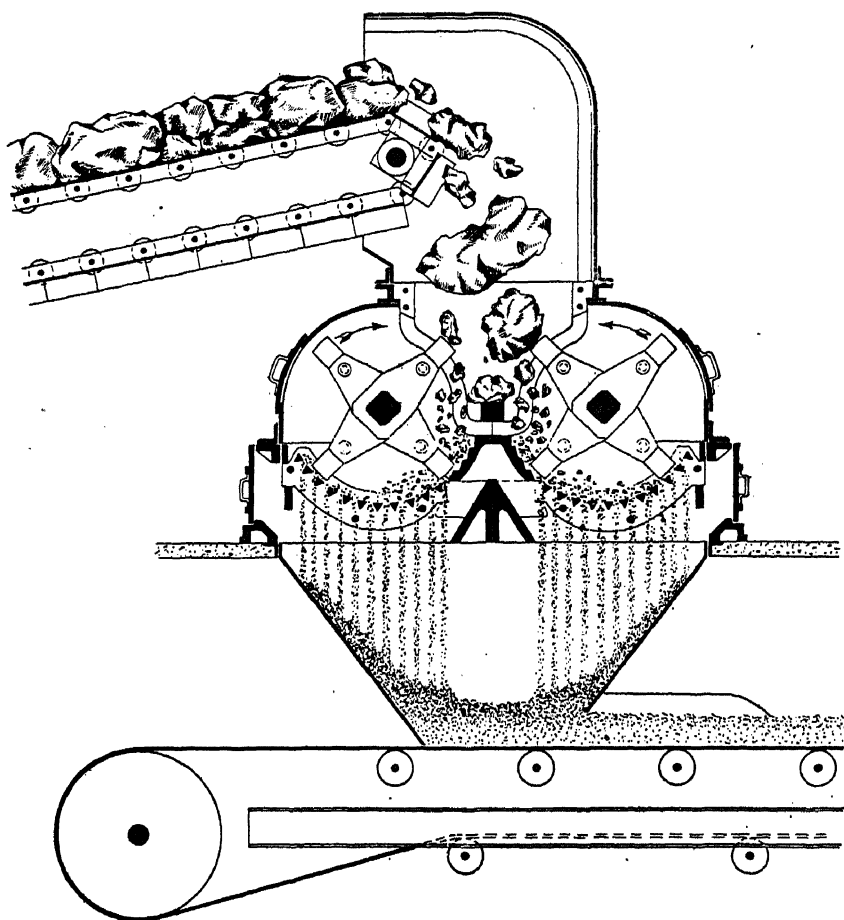


Fig. 33.—Double-Spindle Hammer Crusher.

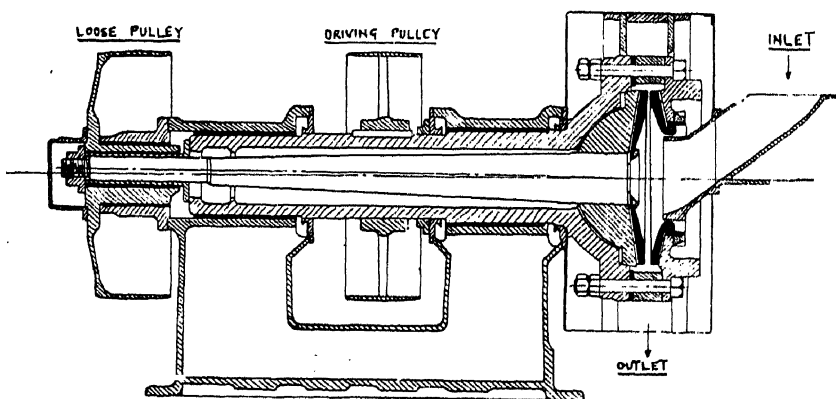


Fig. 34.—Horizontal Disk Crusher.

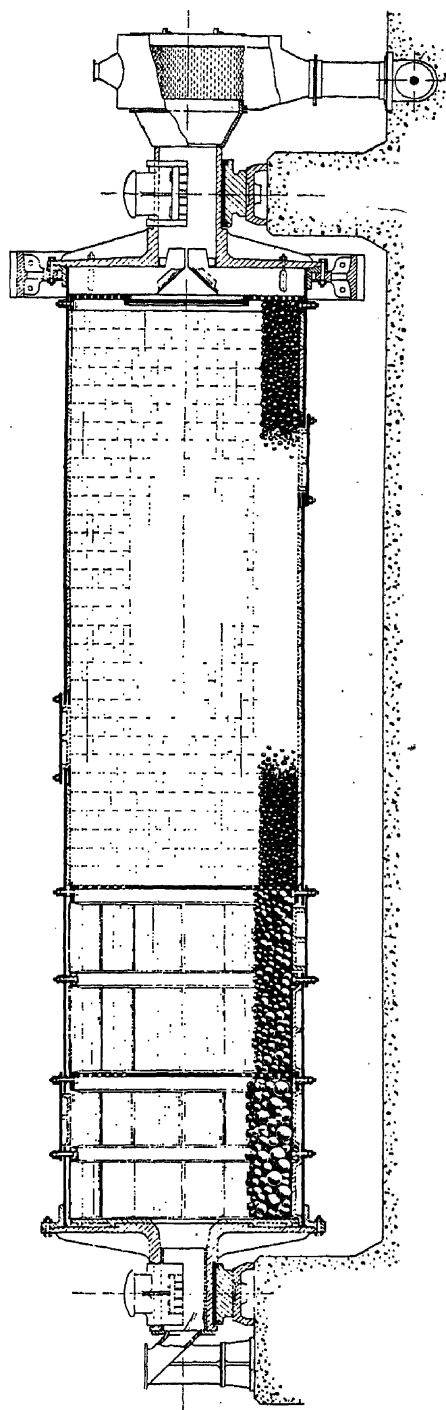


Fig. 35. Single-unit Mill.

like limestone, 34 or 36 per cent. of moisture would be comparable with the 40 or 42 per cent. previously referred to. Water in every case is fed to the mill with the feed.

Too much importance cannot be attached to the consistent fine grinding of the raw materials for making high quality cement. The usual residue on the No. 170 sieve would be 2 or 3 per cent.

The power required to grind the soft variety of chalk and clay to the residue given would be, say, 8 to 10 kW. per ton. The corresponding figure for raw materials



Fig. 36.—Griffin Mills.

of the limestone class ground to the same residue would amount to 35 or 40 kW. per ton, depending upon the hardness and the residue.

In dry process works the raw material is dried and ground dry instead of wet, as previously described. When grinding is carried out dry the power required per ton appears to be rather greater.

The relative advantages of the "wet" and "dry" processes of raw material preparation were discussed at length in Chapter III.

CHAPTER VII

TRANSPORTING AND ELEVATING

THE many processes in the manufacture of Portland cement necessitate a large amount of elevating, conveying, and transporting. The delivery of the raw materials from the quarries is usually effected by railway or ropeway, but the raw material must be conveyed from the preliminary storage to the mills, from the mills to the silos or mixers, and then to the kilns; the clinker from the kilns to the stores and from the stores to the mills; the finished cement from the mills to the warehouse, silos, or other storage, and so on. Elevating is also necessary in many stages of the process.

Dry Raw Materials

With soft raw materials mixed by the wet process the chalk and clay are usually delivered direct into the preliminary washmill, but for dry raw materials the conveyors from storage are usually of the band or belt type (*Fig. 37*), troughed where



Fig. 37.—Belt Conveyor.

necessary to increase their capacity, and uncovered; owing to the nature of the material there is no necessity to enclose them. Conveyors are sometimes installed at a rising gradient where the height is small, to operate as elevators as well as conveyors. The maximum inclination for duty of this kind would be 30 deg., but this steepness should be avoided if possible. The usual linear speed would be, say, 200 ft. per minute for inclined belts, and up to 350 or even 400 ft. per minute for horizontal belts.

The feeding of belt conveyors is usually accomplished by a mechanical device (*Fig. 38*) with the object of obtaining a layer of material of uniform thickness, and the belts are fitted with a skirt-board for a distance of 6 ft. to 10 ft. at the feed end to prevent the material being spilled. Heavily loaded belts are supported upon rollers 3 ft. or 4 ft. apart; this dimension may be increased if the belts are less heavily loaded. Discharge is usually, but not necessarily, effected at the end of the belt, delivery taking place on a chute into a hopper or otherwise, as required.

Intermediate throw-offs are arranged when the material is to be delivered on one side or other of the belt at any intermediate position. This throw-off attachment is movable, and supported upon track wheels which in turn are supported upon the

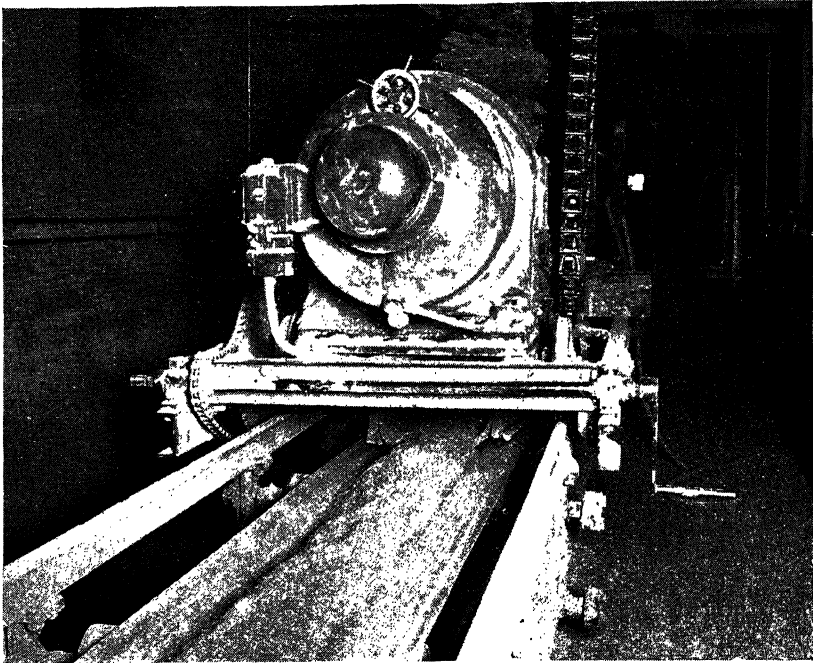


Fig. 38.—Extracting Gear under Silos.



Fig. 39.—Belt Conveyors and Motor-Driven Trippers.

same framework as the belt rollers (*Fig. 39*). Driving is effected by an electric motor with reduction gear, or by a belt and spur gear. The driving end is usually fixed to the supporting framework, the provision for adjustment for variation in

the length of the belt, etc., being made at the far end. If the temperature variation of the material conveyed is small, screw adjustment only need be provided; if, however, the temperature variation is considerable, automatic adjustment must be arranged; this is usually obtained by means of a heavy balance-weight. *Fig. 40* shows a belt conveyor transporting raw material: (a) the feed end with hopper and skirt boards; (b) the discharge end; (c) an intermediate throw-off; (d) a half section through A A showing the troughing of the belt.

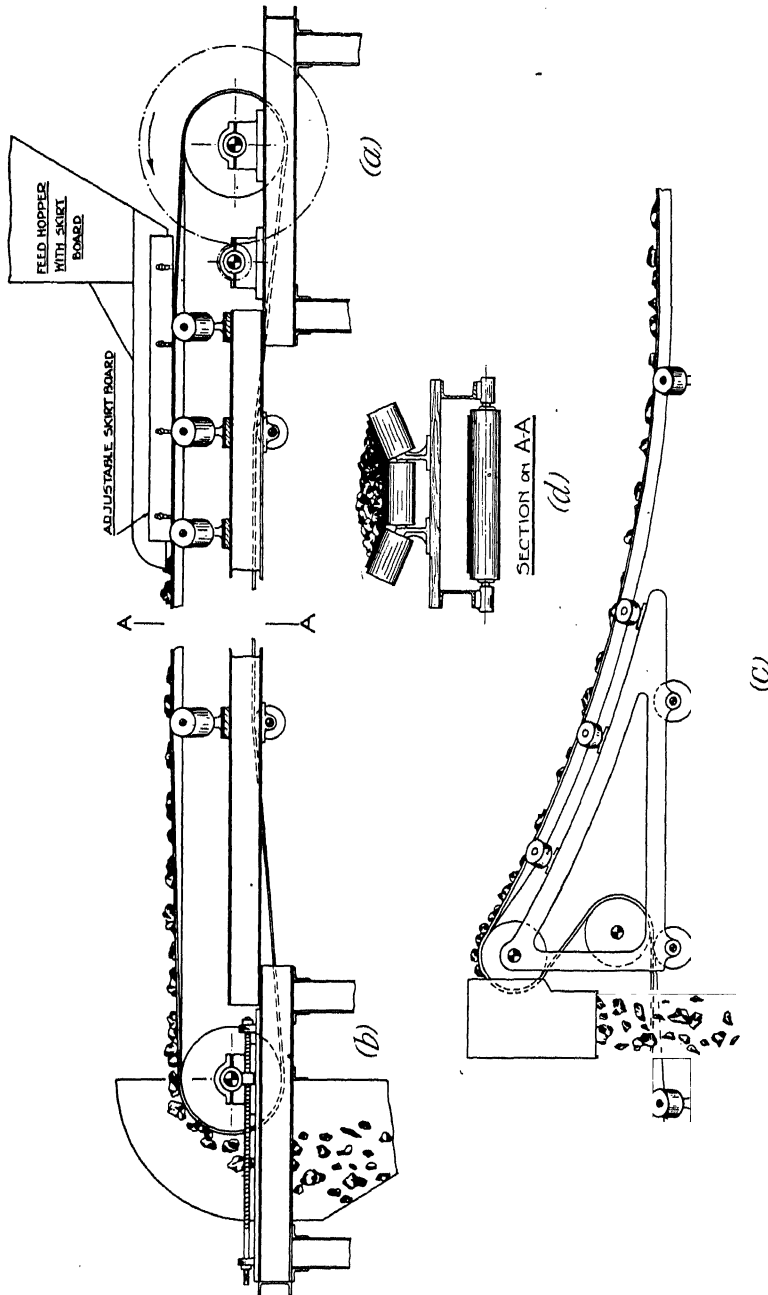


Fig 40 Belt Conveyor

Elevators are generally of the bucket type, operating within casings. Where the material is abrasive it is more usual to use belts as the flexible medium, but link chains are used where the material is not so abrasive. Belts may be either of the woven or canvas type; the latter would be made up into as many plies as necessary for the duty, load, and power. If the material is very abrasive, canvas belts should be protected with a layer of rubber on both surfaces. The buckets may be arranged at from 12-in. to 36-in. centres; where the duty is comparatively small the larger dimension, and where large the smaller dimension, would be adopted. For very heavy duty it may be necessary to place the buckets as close together as possible without interfering with the discharge.

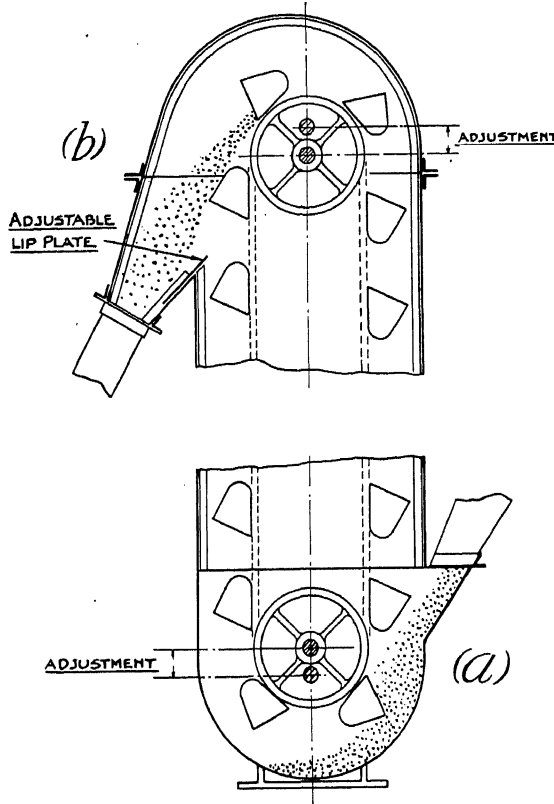


Fig. 41.—Bucket Elevator (See also Fig. 45).

Chain type elevators are adopted for the heaviest loads up to 200 tons per hour. Under these conditions the bucket capacity must be large; the buckets should be closely spaced to obtain continuous discharge, and the chain must be amply strong.

Where belts are used the speed may be up to 450 ft. per minute, the exact speed depending upon the diameter of the head pulley. With chains the speeds should be considerably below this figure. It is easier to take advantage of centrifugal discharge effect in using belts than in using chains.

The lip at the elevator head plays a very important part in controlling the discharge of any type of elevator. The edge of the lip should be set in such a position with reference to the bucket as it commences its downward motion that the minimum amount of return into the boot is assured.

Fig. 41 shows two views of a bucket-type elevator : (*a*) the material entering the boot and being dredged by the buckets; (*b*) the upper part with discharge and lip plates.

Finished or Partly Finished Material

In dealing with finished or partly finished material the same general principles apply, but the work may be carried out in a different way. Bucket conveyors

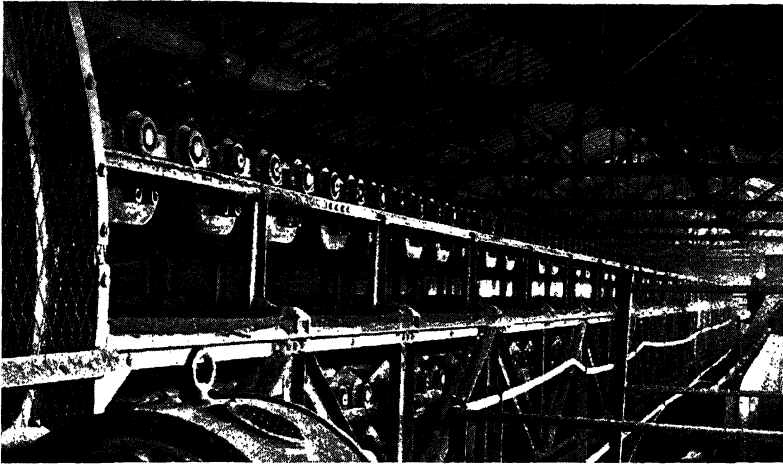


Fig. 42.—Bucket Conveyor.



Fig. 43.—Shaker Conveyor.

(*Fig. 42*) and shaker conveyors (*Fig. 43*) are frequently used for clinker. In the raw material stage the amount of "fines" is very small, and, speaking generally, it is not always necessary to enclose either the elevators or the conveyors. It is not possible to use spiral conveyors for the duty owing to the rapid wear. In the

final stages of manufacture spiral conveyors are mostly used owing to the facility with which they can be totally enclosed and their dustless operation.

Spiral conveyors are manufactured in sizes from 6 in. to 24 in., or even 30 in., diameter if the quantity to be transported is large enough to warrant it. Usually the centre shaft is made of fairly heavy solid-drawn steel tube, and the blading is attached to this tube by welding or by a special form of palm bolt. The usual length of each piece of spiral is 10 ft. or 12 ft., and successive lengths are connected by a supporting journal, which in turn is supported by its bearing attached to, or supported upon, the casing in which the spiral rotates. This casing may be either of sheet steel or cast iron; if, however, the spiral is to be positioned in or beneath the floor, the casing may be of concrete formed in situ, the bearing supports being provided in the same way.

Fig. 44 shows a typical spiral conveyor: (a) a longitudinal section; (b) a cross section showing a mild steel casing; (c) a similar section in concrete casing. The usual speed of the spirals varies from 100 r.p.m. for the small size to, say, 50 r.p.m.

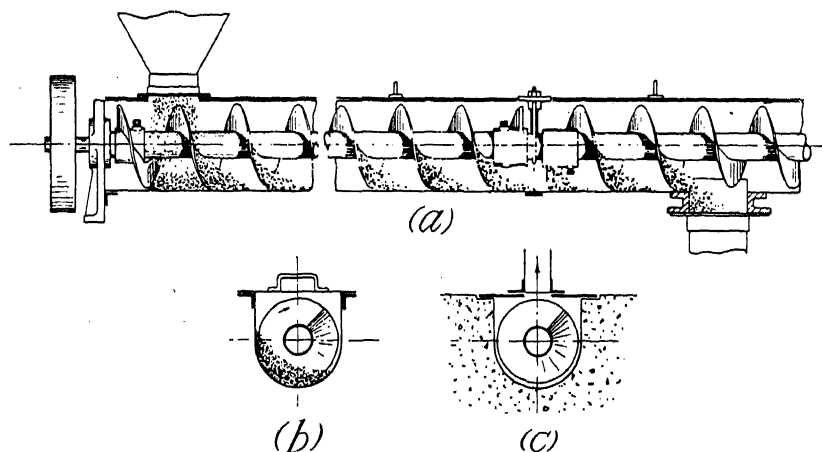


Fig. 44.—Spiral Conveyor.

for the 15-in size, and, say, 30 r.p.m. for the 24-in. size. The 6-in. size at a suitable speed would convey up to 5 tons per hour without difficulty; the 24-in. would convey up to 100 tons per hour. Owing to the constant stirring-up effect of the spiral, it is necessary totally to enclose it whatever the type of casing. Mild steel casing usually has a cover of sheet steel bolted down to the angled edges of the trough. In the case of concrete, it is usual to cover the spiral by chequered floor-plate weighing, say, 10 lb. or 12 lb. per square foot, and the weight is sufficient to keep this plate in position.

It is desirable to keep the surrounding atmosphere free from dust, and to effect this the conveyor casing, whether of steel or concrete, may be subjected to a slight negative pressure by an exhausting fan. This fan withdraws from the casing whatever amount of air is necessary to produce a slight draught inwards. Sometimes the casing is enlarged at the top and takes the form of an inverted trough, thus forming a hood and increasing the air space.

When band conveyors are used for finished cement or dried and ground raw material, it is desirable that the feed and delivery ends should be enclosed as far as possible to prevent dust escaping. This type of conveyor is not generally suitable

for receiving or delivering fine materials at a number of intermediate points, but for carrying from one point to another it can be made entirely satisfactory with attention to detail.

Elevators, especially the larger sizes, are troublesome when dealing with a highly-floured material. Whenever possible they should be of the continuous-bucket type operated at comparatively low speed, and the capacity should be obtained by bucket size rather than bucket speed. Chain belts are in common use for this duty, and the wear and tear have not proved abnormal. Malleable

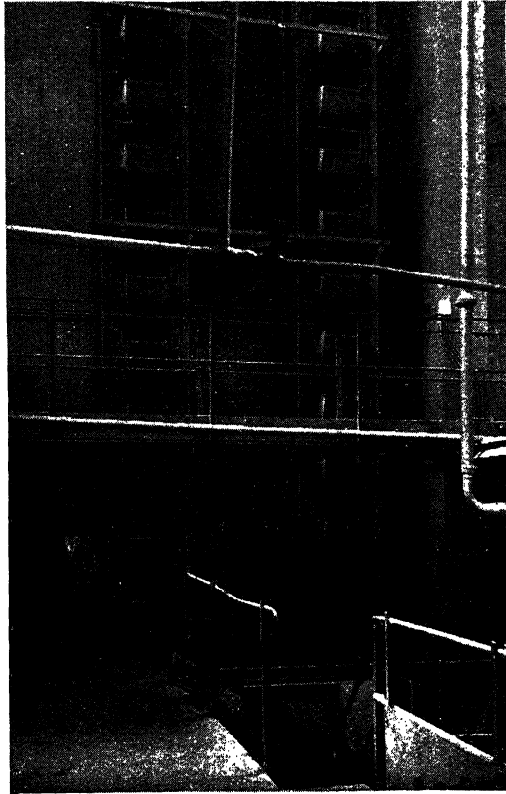


Fig. 45.—Bucket Elevator (See also Fig. 41).

iron links with manganese steel bushes and pins are the materials mostly used, and the performance of parts made of these materials has proved satisfactory.

Pneumatic Pumps

Since silos have come into general use for storing finished cement a difficulty sometimes arises due to the abnormal height of lift. Silos are frequently up to 100 ft. high, and although it is possible to design an elevator for a 100-ft. lift it would be heavy and it would probably be more satisfactory to deal with the total height in two lifts, the discharge of the lower elevator being arranged to deliver into the boot of the upper elevator.

This has led to other methods of elevating and transporting being developed in recent years, and three well-known systems are now working satisfactorily in

which the material is conveyed in air as the carrying medium. Some of these are in use transporting cement over distances up to 3,000 ft. and elevating to a height of 100 ft. Any reasonable combination of this horizontal distance and vertical height is obtainable. These methods of transport are especially suitable for use for indirect routes where ordinary methods would be difficult. In each case the apparatus is described as a "pump" and the arrangements are as follows.

The Fuller-Kinyon pump consists of a short length of cast-steel worm conveyor, a strong spiral rotating at a high speed in a totally-enclosed casing. The cement is fed into the casing at the inlet end of the spiral and discharged into the pipe-line at the remote end; when discharging, it is intimately mixed with high-pressure air through a ring with a large number of holes. As the direction of flow of the air is in agreement with the desired flow of the cement, the cement-air mixture is caused

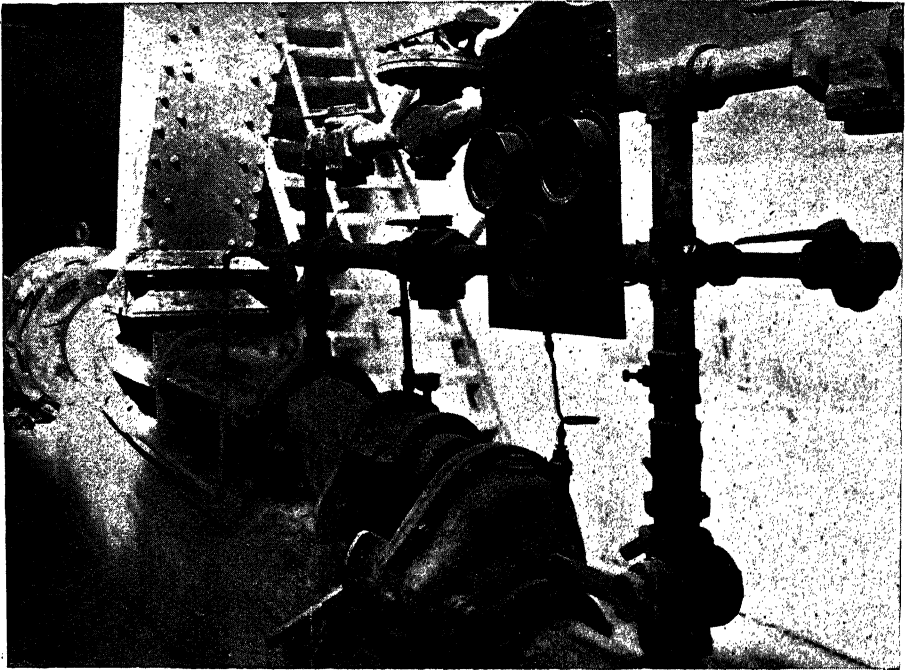


Fig. 46.—Cement Pump.

to flow at high velocity (60 ft. to 80 ft. per second) through the pipeline. No difficulty arises in transporting through a vertical pipeline; difficulties may, however, arise in transporting up a sloping gradient owing to the tendency to "drift" if the velocity or quantity of the air is too low. A velocity of 60 ft. per second is possibly on the borderline of trouble and should be adopted only for very short pipelines. A velocity of 80 ft. per second appears safe for most conditions, but in very long lines the quantity and velocity should both be increased. Fig. 46 shows one of these pumps, and Fig. 47 is a section: (a) the casing; (b) feed inlet; (c) spiral; (d) driving motor; (e) coupling; (f) air ring; (g) discharge opening; (h) beginning of the pipe-line. The power consumption and cost of this method are naturally high for short lengths of transport, but where the length is considerable and the difficulties abnormal it has in many cases proved economic and successful.

The Cera pump, illustrated in *Fig. 48*, operates in a different way. It is usual to have two containers, each of 2 or 3 tons capacity, the exact size depending upon the capacity of the plant. The two containers are filled by gravity alternately through the medium of a spiral conveyor from the source of supply. As soon as container No. 1 is filled the feed is automatically turned into container No. 2, all

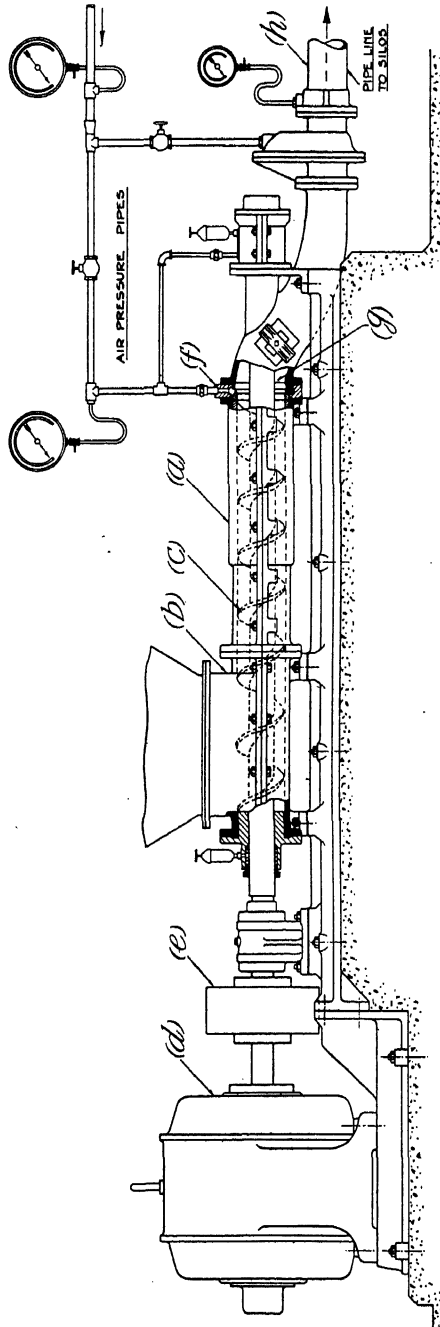


Fig. 47.—Section of Cement Pump.

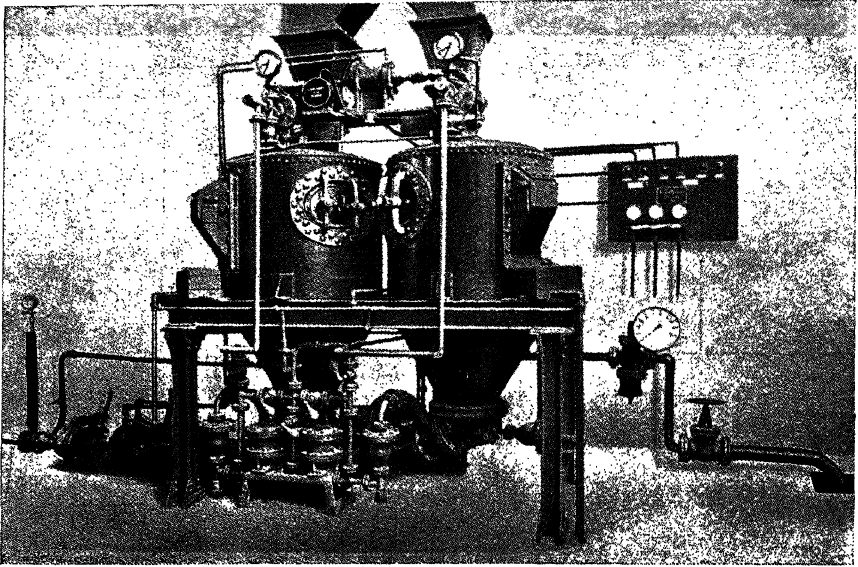


Fig. 48.—Cement Pump.

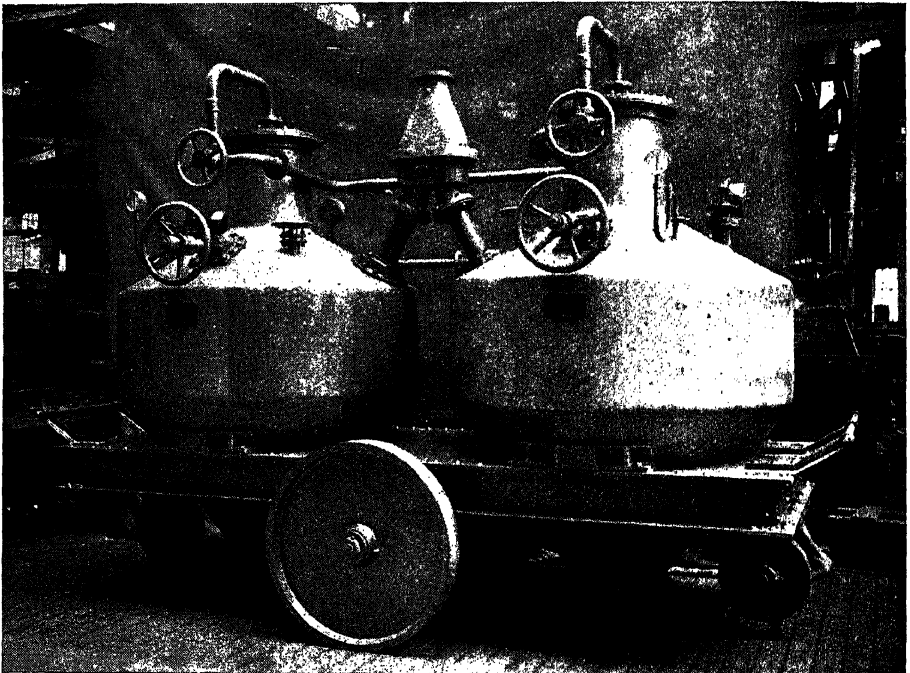


Fig. 49.—Portable Machine, transporting 30 tons of Cement per Hour from Silos to Packer Hoppers.

openings and valves on container No. 1 are closed, the pressure air is turned on, and the cement is forced into the pipeline. When container No. 1 is empty all the valves are reversed ready for filling again as soon as container No. 2 is full. When the rate of feed is about equal to the rate of discharge the process is practically continuous. The process is automatic, but special care is necessary to prevent air leakage in the valves or connecting pipes.

The F. L. S. transporter, shown in *Fig. 49*, is very similar in principle. The same manufacturers have also developed an extractor-transporter unit which extracts cement from silos and discharges it at any desired point. This system requires an air exhauster in addition to the compressor with containers previously referred to. Each container is connected to the silo and exhauster as well as to the air compressor and the point of discharge. The combination of valves and piping enables the air to be exhausted from the container and its place occupied with cement withdrawn from the silo by the vacuum in the container. As soon as the container is full the exhauster valve is closed, pressure air is turned on, and the cement is discharged to the desired point. Normally one or other of the containers is being exhausted of air and filled with cement while the other is being discharged through the operation of the pressure air. This reversal of duty enables the operation of the plant to be continuous, subject to the pauses which occur during the change-over from vacuum to pressure and vice versa. This system also demands the closest attention to the piping, joints, and valves.

CHAPTER VIII

BURNING OR CALCINING: EARLY KILNS

THE burning or calcining of the raw materials at a high temperature and to a point of slight vitrification is the next operation, producing clinker.

In the raw materials the lime is present as carbonate, and the silica, alumina, and iron oxide may be present in the free state, but usually as complex silicates with some of the iron as sulphide. In converting them into cement clinker by burning the silica, alumina, and iron oxide enter into combination with lime forming calcium silicates and aluminates and calcium ferro-aluminate. These are the chief constituents of Portland cement, and the minor constituents are magnesia, alkalis, and sulphur compounds.

The calcining process is a purely chemical one, and, if not properly carried out, may destroy the value of the finished product. If the temperature is too high the kiln is damaged and fuel is wasted; on the other hand, if the heat is insufficient the necessary chemical changes do not take place. Satisfactory burning is indicated by the formation of a dense greenish-black clinker. Lightly burned clinker is yellow or brown in colour and soft, while over-burned clinker is fused and slag-like. Excess of clay or imperfect mixing may cause the clinker to "dust" or fall to powder on cooling, but this defect was much more common in the earlier vertical kilns than with modern rotary kilns, as the better control of burning by the latter process is most beneficial in the production of good and uniform clinker.

The temperature obtained in the kiln for normal Portland cement (76 to 77 per cent. CaCO_3) is about 1,400 deg. C., or, say, 2,550 deg. F. A reduction in carbonate of lime reduces the calcining temperature slightly, but it may be said that the temperature usually required to bring normal raw materials to the point of incipient fusion is about 2,500 deg. F. The higher the percentage of lime the higher the temperature necessary to produce complete combination with silica, and the greater the necessity for a large surface area of contact. The finer the grinding of the raw mixture the higher the percentage of lime that can be carried.

A proper chemical composition of the raw materials is no guarantee that the resulting cement will be satisfactory, because if they are not properly burned the materials may not have attained thorough combination, and consequently may not reach equilibrium at the burning zone temperature. It is essential that the closest attention be given to the burning operation, which is a process requiring experience and care.

Until recent years the burning of cement has not had close attention and study from a scientific point of view, but with the advent of the rotary kiln better facilities were afforded for such investigation, and much knowledge and practical improvement to-day arise from the use of this method of burning. Before describing the more modern methods of burning it will be of interest to review briefly the earlier methods, and it will also assist a better appreciation of the evolution which has taken place.

Early Kilns

Kilns for burning cement in the old days were of either an "intermittent" or a "continuous" character, among the earliest being dome or "bottle" kilns (*Figs. 51 and 52*), followed later by chamber kilns and others to which the names of the

designers were sometimes applied, such as Batchelor, Johnson, Dietsch, Hoffman, Aalborg, Stein, Schneider, and, lastly, the kiln now generally adopted—the rotary kiln. Burning in intermittent kilns necessitated distinct loading and drawing operations, the kiln being stopped during the drawing of the clinker and recharging with the next load. The loading, burning, and drawing of the intermittent kiln occupied some five to six days. This method is now quite obsolete. In continuous

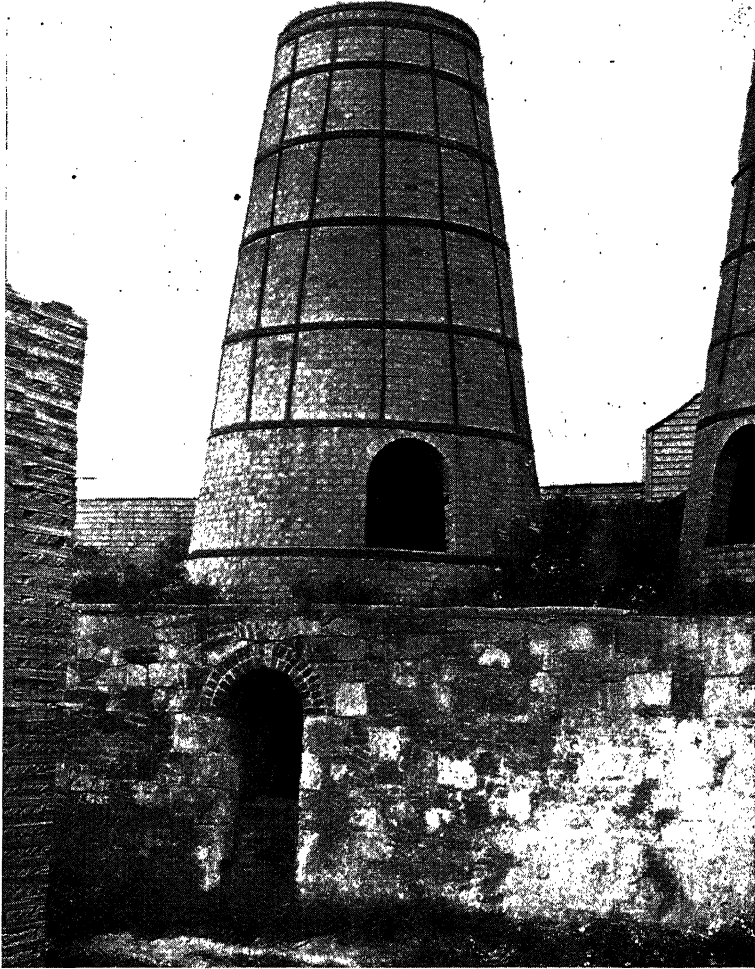


Fig. 50.—Early Kiln used by Aspdin's Son at Northfleet.

kilns the burning of the raw material is continuous, the loading of the kiln and the drawing of the clinker taking place at the same time while the burning proceeds without interruption, thus making a continuous process. Continuous kilns are generally costly to construct and require skilled labour for their operation. These kilns were, however, economical in fuel, and when they succeeded the intermittent kiln the calcining process became much more regular and the cement of better quality.

INTERMITTENT KILN.—The intermittent dome kiln was originally the only type employed in the industry. The consumption of coke (the fuel used) amounted to about 40 per cent. of the weight of clinker produced. The first step in loading bottle or dome kilns, and also chamber kilns, was the careful arrangement of faggots on the bars of the kiln to start the fire, followed by alternate layers of coke and raw material, which had become solidified by settlement in "backs," until the kiln was filled, the layers of fuel and raw material gradually decreasing somewhat in thickness towards the top. In this way the heat was distributed more regularly over the kiln when it was fired. In this method of burning the following sequence of events took place: When the coke became ignited by the firing of the faggots the moisture from the raw material was expelled, and with the subsequent red heat



Fig. 51.—Bottle Kilns at Robins & Aspdin's Works at Northfleet, Kent.

the carbonic acid gas was driven off. The final stage in the burning was approached when the temperature increased to almost a white heat of 2,000 deg. F. to 2,500 deg. F., causing the material to become slightly vitrified. Layer after layer of the raw material was thus calcined into clinker. With the intermittent kilns this process went on until the whole of the contents of the kiln was burned through and the clinker had then to be allowed to cool before the unloading of the kiln took place, an operation which was very hot and laborious for the men.

The kiln was of the simplest type of construction. The chamber was usually egg-shaped. The estimation of the proper amount of fuel required experience, since the draught varied with the prevailing wind, and this method of burning was more or less at the mercy of the elements. The amount of over-burned and under-burned

clinker was proportionately large and the output small. The cost of labour and fuel was very high.

CHAMBER KILN.—The chamber kilns were undoubtedly a great advance on the earlier kilns, economy being effected by the hot gases from the fire passing over wet slurry previously spread on covered floors, and drying it for the next charge ; the kiln proper was at one end of the covered floor or chamber and the chimney stack at the other. These kilns were also intermittent, and only produced a small output with considerable labour and fuel. Trouble was also likely to occur if the burner lacked experience. If the proportion of water in the slurry was not kept low the drying was retarded by the excess water. Again, if the “slip” put into the kiln was not dry the moisture when driven off condensed on the surface of the slurry in the chamber, and had therefore to be expelled before the drying of the slurry

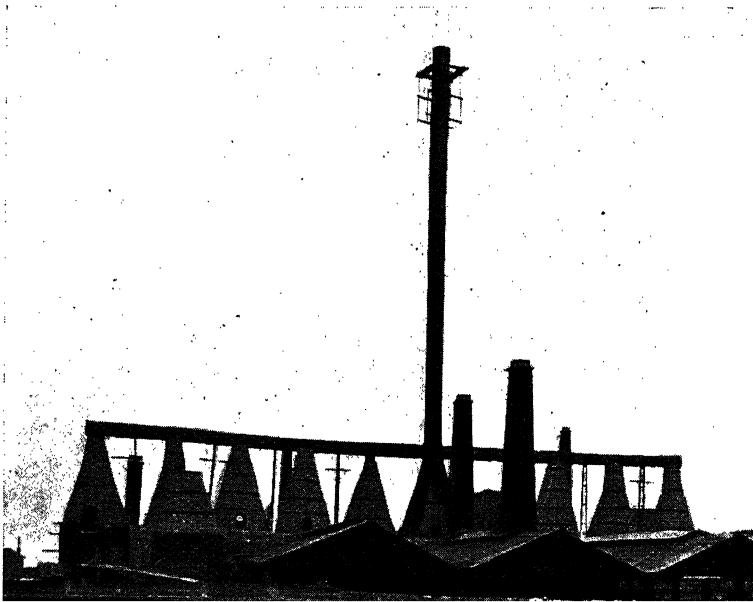


Fig. 52.—Early Bottle Kilns Connected by Common Iron Flue to an Iron Chimney.

commenced. Then there was the possibility of the “slip” falling away to dust in the kiln and interfering with the draught. The gases sometimes accumulated above the kiln, and the air drawn in through cracks, which always appeared in the brickwork from expansion caused by the heat, formed an explosive mixture which, as soon as the fire appeared on the top of the kiln, was ignited, with the result that the ends of the kiln were blown out. It was advantageous with these kilns to carry away the gases and steam, without passing them over the slurry, until the kiln “dropped,” or, in other words, until the fire broke its way through the material in the kiln. If this was done 2 ft. of slurry in the drying chamber could be dried in twenty to thirty hours by careful regulation of the draught. These kilns were usually designed to give about 30 tons of cement at each charge, and draught was provided by a chimney which was sometimes quite short. Given ordinary attention, however, a good

cement was manufactured by this process, which sufficed in the industry for some decades.

BATCHELOR KILN.—The Batchelor kiln was constructed on somewhat similar lines to the chamber kiln, with the difference that instead of the single drying chamber a series of slurry-drying chambers was provided at the back of the burning portion of the kilns by two or three arched chambers arranged one above the other (*Fig. 54*). One big chimney usually served for a block or group of kilns. The Batchelor kiln again was costly in labour and fuel (coke), although giving good results.

CONTINUOUS KILN.—With the continuous kilns formerly used in England the heat was kept up by the regular feeding of the coal or coke with the raw material. The principal difference between what may be described as the old method and the

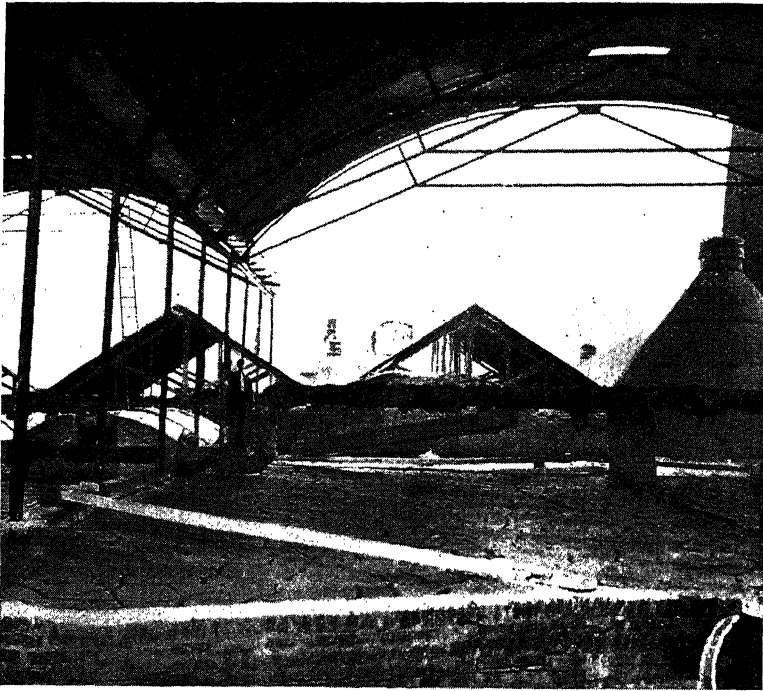


Fig. 53.—Slurry Drying Floors.

continuous kilns here referred to was that instead of burning the kiln right out, cooling off, and drawing all the clinker each time, the burning rarely ceased except for repairs ; this showed considerable economy, since the heat was constant and the cold air travelled up through the burnt clinker at the bottom of the kiln, which it cooled, and was at the same time itself heated on its way to the fire zone. In turn the heated gases leaving the fire zone parted with the greater portion of the heat to the raw material travelling downwards (towards the fire zone) when passing through the kiln on the way to the chimney. The economy of a continuous kiln of this type was shown by the low temperature of the gases when they reached the chimney, the reduction being so great that although the temperature must have been some 2,500 deg. F. at the fire zone of the kiln the hand might easily be held in the gases leaving it. There is no doubt that a considerable saving of fuel (some

50 per cent.) was effected by the adoption of the continuous type of kiln, as great loss was involved in the constant cooling and heating in the interval between unloading and loading of the older kilns previously mentioned.

DIETSCH KILN.—The Dietsch kiln, though never in general use in England, was one of the examples of the early continuous kiln. The dried slurry, or raw material in the form of bricks, was introduced at the base of the stack into what may be called the heating chamber, which was always full. Below this was a right-angle flue with a short horizontal section over which the hot slurry was drawn by long shovels to fall into the burning chamber, after which it was fed with a layer of coal by hand labour. The burnt clinker in the bottom part of the kiln was cooled by the air entering through the grates, while the slurry in the upper chamber was heated by the gases escaping from the burning zone. At intervals a portion of the clinker, partially cooled, was removed at the bottom, causing a general settlement

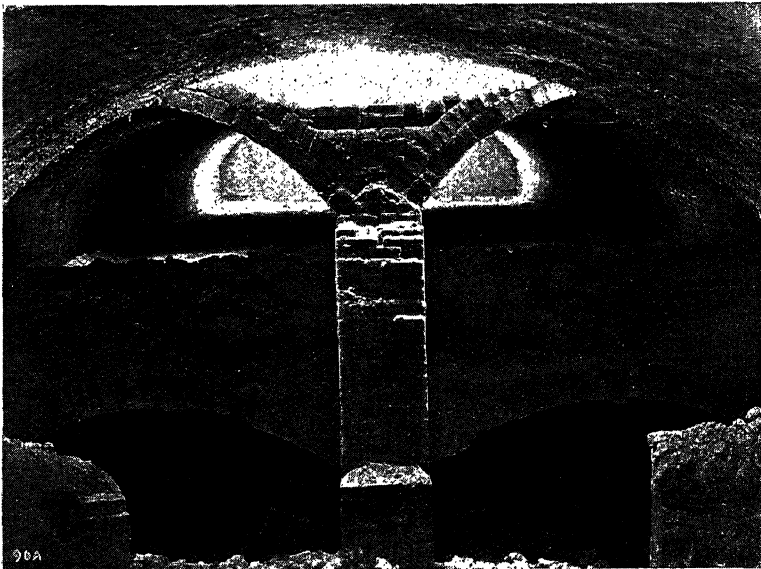


Fig. 54.—Drying Chambers of Batchelor Kilns.

in the kiln and leaving a space at the top into which the dried slurry was raked and more fuel added as described. This kiln took small coal for fuel and was more economical than the intermittent types, using only some 20 per cent. of coal upon the weight of clinker produced.

HOFFMAN KILN.—The Hoffman kiln met with very little success in this country, as the wet process of manufacture was generally adopted, and the kiln was essentially designed for the dry method. It consisted of a series of compartments built around a large central stack, and communicating by means of flues in such a way that the smoke and hot gases from one chamber might be passed through others before reaching the chimney. The kiln might be either "up draught" or "down draught" according to the direction in which the heat was drawn through the chamber. The compartments were charged from the sides, and when the moisture had been driven off from the material in the chamber first fired, the gases from this chamber were passed through the adjacent chamber, which had in the meantime been filled with

raw material. Although this kiln was economical of fuel if run continuously, much labour was required to charge and empty it.

AALBORG KILN.—The Aalborg kiln used on the Continent was almost unknown in England. It consisted of an upper heating chamber and a central combustion chamber of reduced diameter. The construction was carefully arranged and the chimney was carried on the outer walls of the kiln to allow for the contraction and expansion in working the kiln, which thus had little if any effect upon the life of the kiln body. The firing holes were placed at intervals around the kiln and slanted downwards so as to deliver the coal below the clinkering zone. It was claimed that cement was successfully burnt in this kiln with an expenditure of coal equal to some 15 to 20 per cent. of the clinker produced, whilst the labour involved was also said to be small compared with other kilns of the period.

STEIN KILN.—The Stein kiln was made up of a number of concentric cast-iron rings, laid one on the other to form a parallel tube about 40 ft. high by about 8 ft.

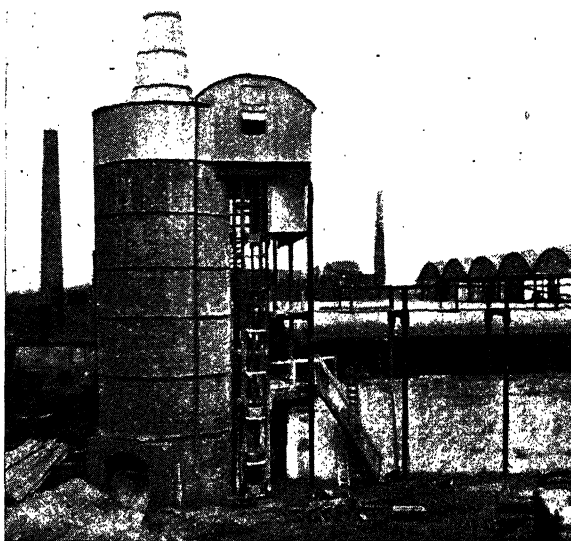


Fig. 55.—Schneider Kiln Adapted for Burning Surplus Slurry from Chamber Kilns (shown on right).

internal diameter, the inside surface being smooth and the outside formed as a series of vertical gills for the purpose of keeping the rings cool and preventing them from burning or melting. The bottom of the kiln was fitted with bars in such a way that the clinker could be drawn when wanted, and yet kept sufficiently open to provide the necessary draught. Doors were fitted so that the bottom of the kiln could be made air-tight in order to use forced draught supplied by a fan if desired. A chimney some 4 ft. in diameter and 10 ft. high drew away the gases from the top of the kiln. The Stein kiln was economically worked in connection with the dry process, burning dry or even damp bricks. The clinker was drawn at four to six hour intervals, and the kiln was reloaded in alternate charges of ordinary gas-coke and bricks (the usual charge of the latter being 20 cwt. to 22 cwt. of dry raw material) from a stage on the loading level.

SCHNEIDER KILN.—The Schneider continuous kiln (*Figs. 55 to 60*)—known also as the “shaft” kiln—was perhaps the most popular of the continuous type

in England. It was operated in a similar manner to others of the type, the layers of raw material and fuel being fed into the top of the kiln at the same time that the clinker was drawn from the bottom. The fire zone occupied about the middle third of the shaft, the layers of raw material and coke being contained in the upper portion and the clinker in the lower.

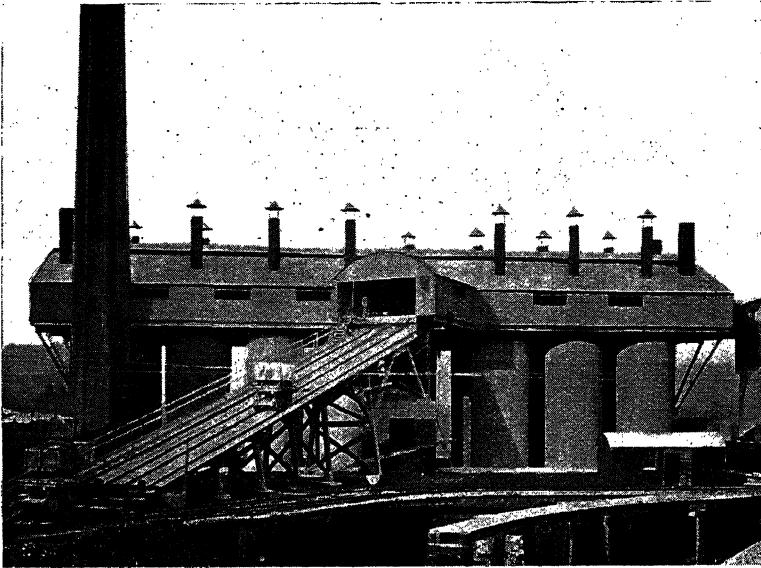


Fig. 56.—A Battery of Schneider Kilns.



Fig. 57.—Charging Floor of Schneider Kilns.

The Schneider, or shaft, kiln consisted of a brick or concrete cylinder usually 16 ft. in outside diameter and 40 ft. in height from the ground floor to the loading floor. The inside diameter was about 9 ft. The kiln, before being first lighted up, was loaded with bricks or stones to about half-way up, and the preparations for the fire were made. The loading of the coke and raw material proceeded, and the fire

started through a space left while loading. When the raw material had burned through the drawing of the "packing" from the bottom commenced and simultaneously further loading of coke and raw material layers proceeded at the top.

Clinker appeared at the bottom of the kiln in about three days, and the continual drawing and loading then proceeded about every four hours night and day. The upper heating chamber was fairly large, but the hot zone was relatively small and did not extend over a vertical height of more than 5 ft. or 6 ft. The firebrick lining required to be protected with care, and a filling ring was designed to enable the burner to surround the raw material with a protective belt of finely-broken

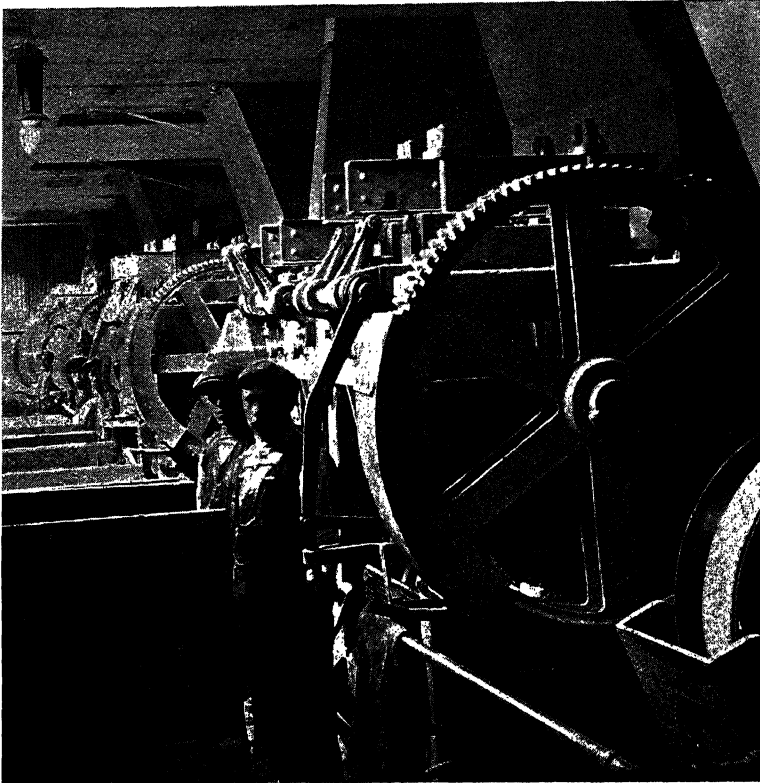


Fig. 58.—Presses for Briquetting Raw Materials for Schneider Kilns.

slurry or raw flour about 2 in. in thickness, but in practice this ring was little used. This kiln, even in its early form, was both easy to work and very economical in fuel. The yield of clinker might vary from 10 to 12 tons per day, and the coke required would be from 28 to 36 cwt. for this quantity. It was not a very expensive kiln to build, and the cost of repairs was relatively trifling provided care was taken with the linings. In more recent times the kiln was fairly popular in this country for burning cement bricks made by the dry process, which might be put into the kilns direct from the machines, and in some works which used the wet process such kilns were employed for burning surplus slurry from the chamber kilns. Burning with the Schneider type of continuous kiln is still carried on to some extent, but considerable modifications of the original design have been introduced. In the later

processes the raw materials are fed into the cylindrical kiln, and the clinker extracted, by mechanical means.

Another method of working the same kiln is to mix together the raw material and coal or coke-duff and mechanically load the mixture in blocks. The class of coal in this case must be good in order to burn quickly and cleanly in the clinkering zone, and thus enable the necessity for picking of underburnt material from the clinker to be dispensed with. The clinker, which appears partly in small blocks and partly in pieces of the size of a walnut, has in later practice to pass through a revolving grate in the bottom of the kiln into small trucks or automatic conveyors, and the output of the kiln by this method is substantially increased. The grinding of the resultant clinker is done by ordinary mills with the greatest ease, as the porous

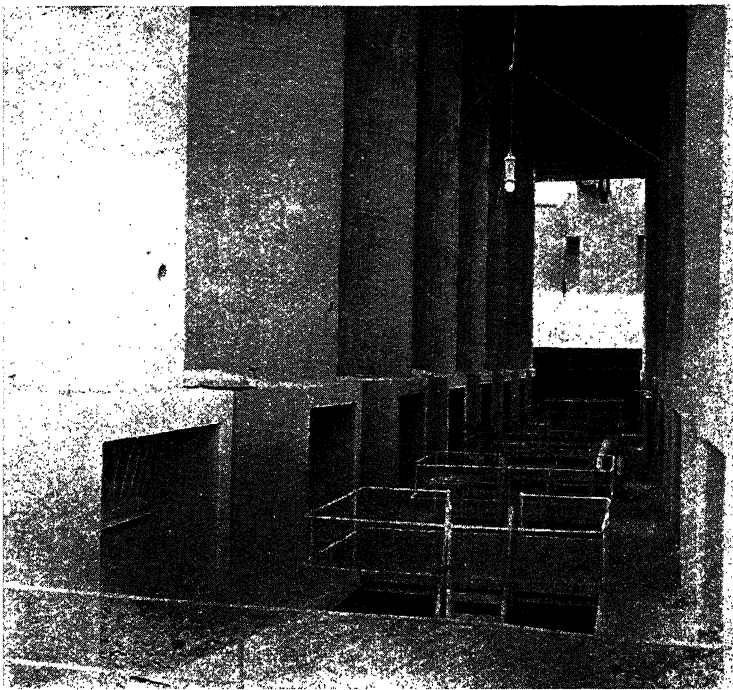


Fig. 59.—Drawing Clinker from Schneider Kilns.

state of the product makes it easier to grind than almost any other clinker, thus effecting saving of power necessary for grinding.

The faults of the original Schneider kiln were the high labour cost (though no higher than with other systems mentioned) and the dependence upon coke fuel. With the improvements mentioned and the introduction of forced draught these drawbacks are done away with, and the advantages of the system, such as cost of plant, less expensive fuel, self-drying of raw materials, small labour cost, substantially increased output, as well as the possibility of working the kiln by hand in case of machinery stoppages, gave a new life to this kiln, or, more strictly speaking, to a new process of burning with a shaft kiln.

It is natural that every manufacturer should be on the look-out for improvements in kilns for cement making, not only to simplify the working and increase

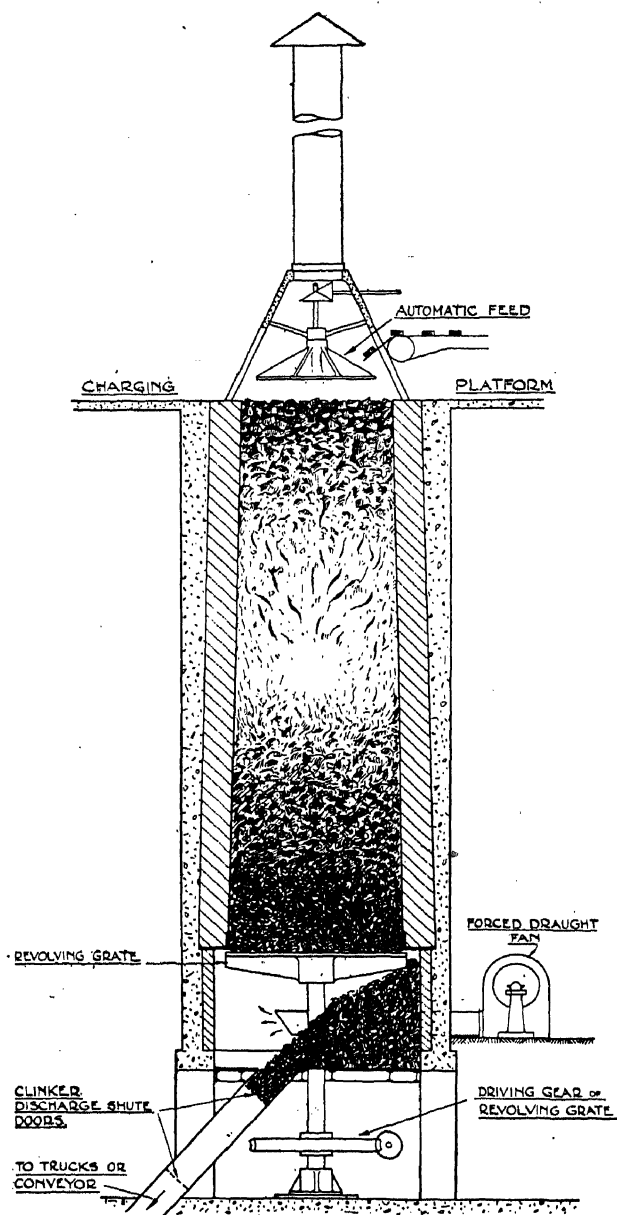


DIAGRAM REPRESENTING SHAFT KILN WITH
AUTOMATIC FEEDING & DISCHARGE ARRANGEMENTS

Fig. 60.

the output but also to effect greater economy in fuel. The earlier Schneider kiln offered advantages in these respects, not only by the smaller cost of plant but also by the better command of the burning operations, although it had the disadvantage that it necessitated the use of a dear fuel (coke) and required a large staff of trained men to work it. These drawbacks the later developments have removed to a very large extent and, more particularly abroad, the forced-draught shaft kiln with the improvements described was given a new lease of life.

All the continuous kilns mentioned could be used for wet-process raw materials, but required drying arrangements by which the slurry might be dried sufficiently to allow of its being moulded into blocks. The amount of fuel necessary for drying is usually somewhat greater than that needed for burning, so that the total amount of fuel required, viz. 30 per cent. to 35 per cent. on the clinker, is not much smaller than was needed for chamber kilns, but a cheaper kind of fuel, namely, small coal, could be used. In the dry process, however, the continuous kilns show to more advantage.

CHAPTER IX

THE ROTARY KILN

THE rotary kiln now generally used has revolutionised the industry, and is the most scientific and practically efficient burning process introduced in the manufacture since Portland cement was first known. The rotary kiln is the only invention of importance in the manufacture since the introduction of ball and tube mills for grinding. That further improvements have occurred and will occur, however, goes without saying, for the manufacture of Portland cement of high quality is a process involving heavy capital outlay, high cost of production, and continuous plant upkeep. With the present kilns there is certainly a demand for more fuel economy, to say nothing of other improvements which will no doubt be introduced as experience proves the necessity and time gives the opportunity. To advocate the use of rotary kilns is unnecessary, since rotary-kiln cement now holds the field to the almost entire exclusion of cement burned by other methods.

The product from the rotary kiln has a distinct advantage in quality both for strength and freedom from any tendency to expansion. This is to be expected, for

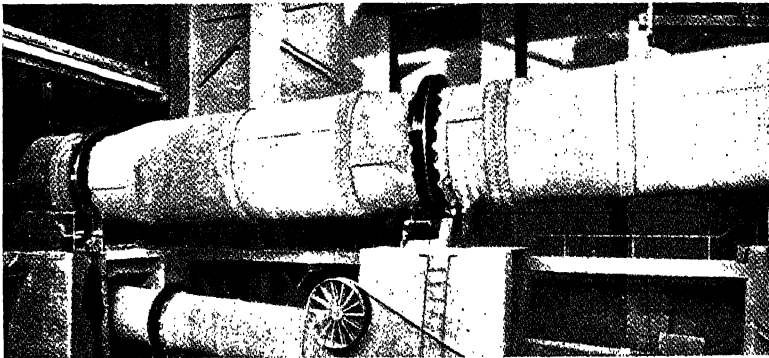


Fig. 61.—Rotary Kiln with Enlarged Burning Zone.

apart from its economy in working the great advantage of this kiln is that the process of clinkering is in full view of the operator and can be controlled by him with exactness. By altering the rotating speed of the cylinder, by decreasing or increasing the feed of the raw mixture, or by varying the force of the coal blast and the quantity of fuel, the burner is able to regulate the burning to any desired degree. With the old-fashioned intermittent kiln no such adjunct was possible, for when once the kiln was charged and fired the calcining proceeded automatically for better or worse.

The rotary kiln as applied to cement burning consists of a slightly-inclined cylindrical tube of steel plates about $\frac{3}{4}$ in. thick. The length ranges from 100 ft. to over 500 ft., and the diameter from 6 ft. to 14 ft., according to the output required from the kiln. Table VII gives the dimensions and approximate outputs of a number of typical kilns on the wet process. The diameters given are those of the greater part of the length of the kilns, but in addition nearly all modern kilns have an enlarged burning zone with a diameter of 1 ft. or 2 ft. greater than the rest of the kiln (Fig. 61).

TABLE VII

					Tons per hour.
100 ft. length by	6 ft. 0 in. diameter,	approximate output			2
150 ft. „	7 ft. 6 in. „	„ „ „			4 $\frac{1}{2}$
200 ft. „	9 ft. 0 in. „	„ „ „			8
230 ft. „	9 ft. 6 in. „	„ „ „			9
250 ft. „	11 ft. 0 in. „	„ „ „			15
300 ft. „	12 ft. 0 in. „	„ „ „			20

The long cylinder is inclined to the horizontal about 1 in 25 or 30, and is mounted on four or five sets of tyres (according to length) which run on heavy rollers. The kiln is slowly rotated by a train of gear wheels at a speed of about one revolution per minute (*Fig. 62*). At the point of the kiln where the tyres and gearing are fitted the tube is reinforced by additional plating. The operation is shown in *Fig. 64*.

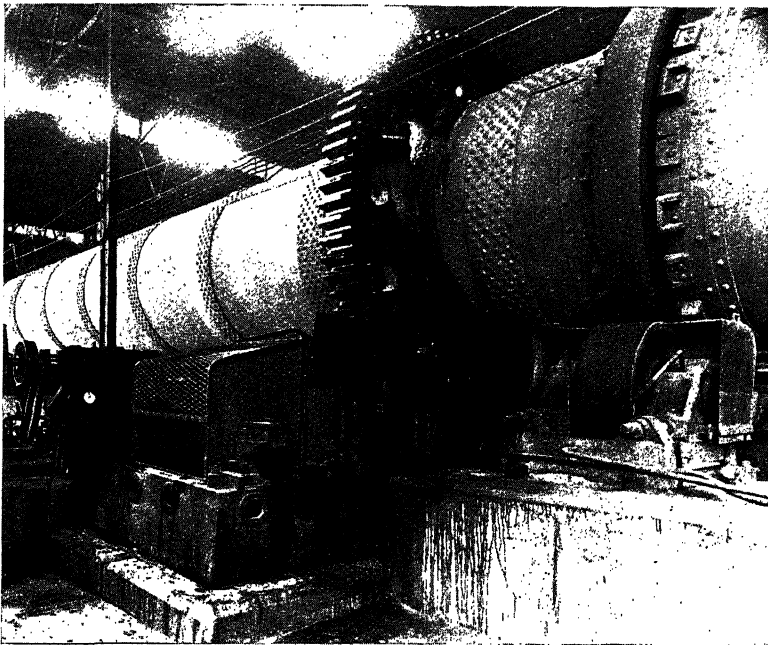


Fig. 62.—Rotary Kiln Driving Gear.

The materials are continuously fed into the kiln at the upper end in the form of either wet slurry or dry powder, according to the process adopted in preparing and mixing the raw materials, and travel by gravity from one end of the kiln to the other. Slurry sprays or lifters are fitted to spread the materials on entering the kiln and when meeting the hot gases. In England finely ground coal is used as fuel, and this is introduced into the lower or outlet end of the kiln by a jet of air issuing from a blast fan. When the kiln is started the fine coal is ignited and a white heat is obtained in the lower end of the cylinder. The raw material fed into the kiln from the opposite end gradually descends into the zone of heat generated by the combustion of the finely-ground coal. First, the material parts with any water that may be present, becomes heated to redness as it approaches the centre of the cylinder, loses its carbonic acid, forms little rounded balls which reach nearly white

heat in the lower end, and finally issues as well-burned clinker in grains about the size of a large pea. The greatest heat is naturally near the fuel jet, or outlet end of the kiln.

The proportionate dimensions of the rotary kiln have been the subject of discussion throughout the history of the kiln. The early kilns were of the same diameter

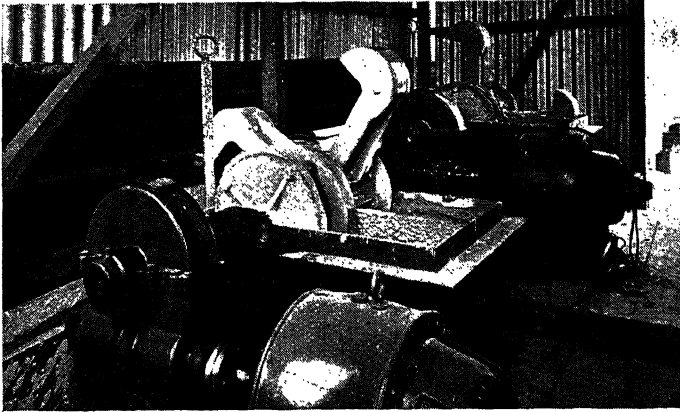


Fig. 63.—Slurry Feed to Rotary Kilns.

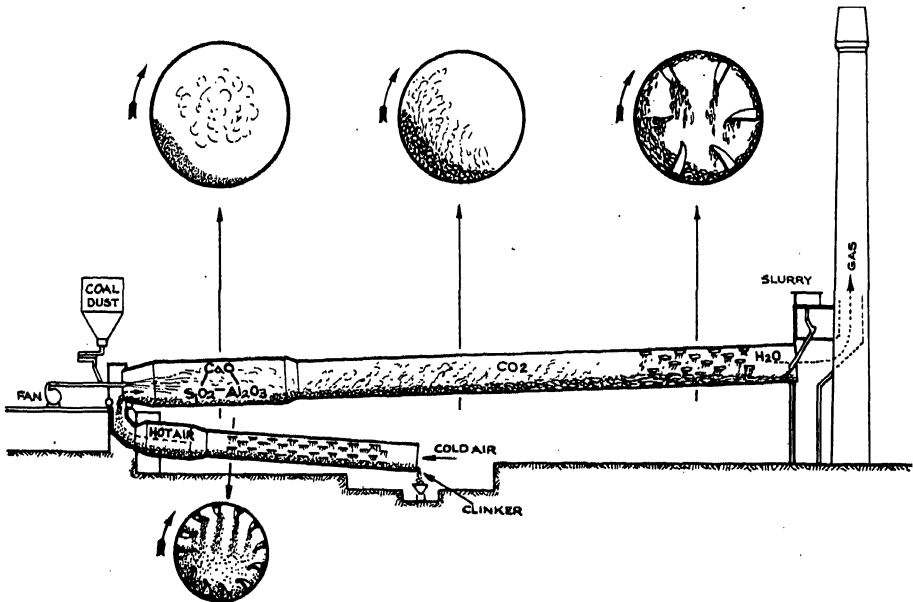


Fig. 64.—Operation of Rotary Kiln.

throughout their length, but in the first decade of this century the designs were modified. First the "slurry end" was enlarged (Fig. 65), and secondly a length of 20 ft. or 30 ft. in the hotter end of the kiln, known as the "burning zone," was enlarged in diameter by 12 in. or 18 in. (Fig. 61). The objects of this enlargement were two-fold: first to provide a larger space for what was thought to require the

greatest amount of room, namely, the drying of the raw materials, and secondly to increase the output of clinker and mitigate the evil arising from clinker rings. Clinker rings are accumulations of clinkered material upon the firebrick lining of the kilns which steadily gather, in some cases to a thickness of 1 ft. or 2 ft., and finally to such a degree that the material can no longer gravitate down the kiln, and the operation of the kiln has to be stopped. The larger the diameter of the burning zone the more the space available for clinker rings if they form, and the less hindrance these rings present to continuity of running. The enlarged burning zone has persisted in rotary kiln design until the present day, and the tendency now is to make it 2 ft. greater in diameter than the remainder of the kiln.

During the last few years enlargement of what is called the "calcining zone" has been recommended in some quarters, and is actually practised (*Fig. 66*). The object of this enlargement is to provide additional space for what is now generally agreed to be the severest operation in a rotary kiln, namely, the decomposition of carbonate of lime. This is an operation that requires a minimum temperature of

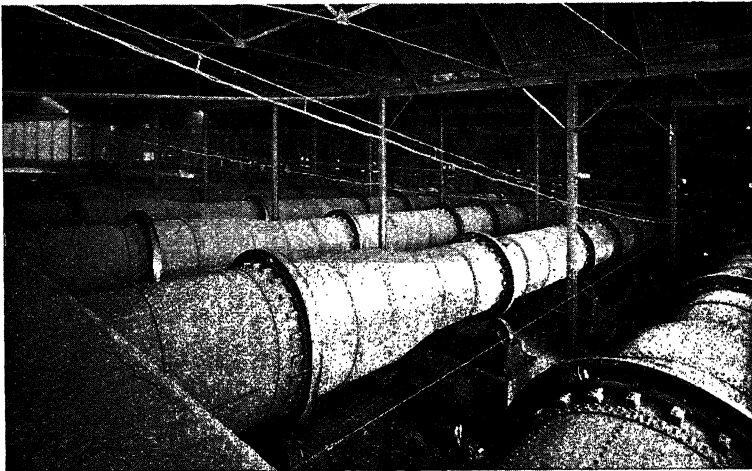


Fig. 65.—Rotary Kilns with Enlarged Slurry Ends.

about 1,500 deg. F. and absorbs a very considerable amount of heat, indeed far more than is absorbed in the clinkering operation. The calcining zone is situated next to the burning zone and almost in the middle of the kiln. There has been some sort of compromise between the adherents of the enlarged burning zone and those of the enlarged calcining zone, which has resulted in an unusually long enlarged zone which is partly a burning and partly a calcining zone.

The idea that the drying zone of the kiln is one calling for additional space has been recently revived, and some kilns have again been designed with enlarged slurry ends, i.e. the upper end of the kiln into which the slurry is fed. In the early years of rotary-kiln development the designers concentrated upon output more than upon heat efficiency, but of late years more attention has been given to improvement in heat efficiency as well as output.

Dealing with the developments of the rotary kiln in general, it will be obvious that the larger the kiln the less the labour cost per ton of output, because a rotary-kiln attendant can attend to two or more kilns with an output of 20 tons per hour

each, while a single kiln of only two or three tons per hour requires the same amount of personal attendance.

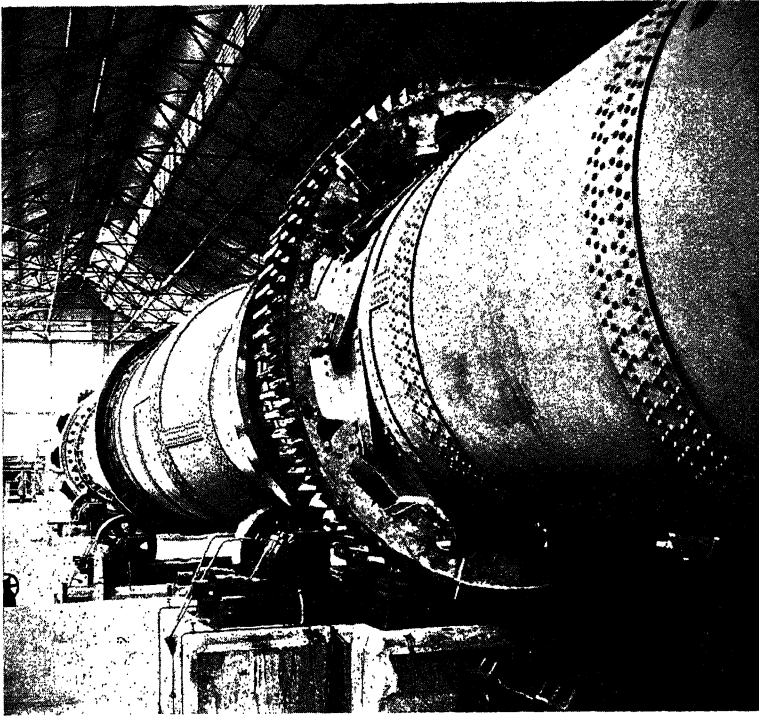


Fig. 66.—Rotary Kiln with Enlarged Calcining Zone.

Clinker Coolers

The red hot clinker from the rotary kiln is cooled in such a way that the air heated by this cooling can be utilised for combustion. The older rotary kilns are arranged with coolers immediately below them, and the clinker falls directly from

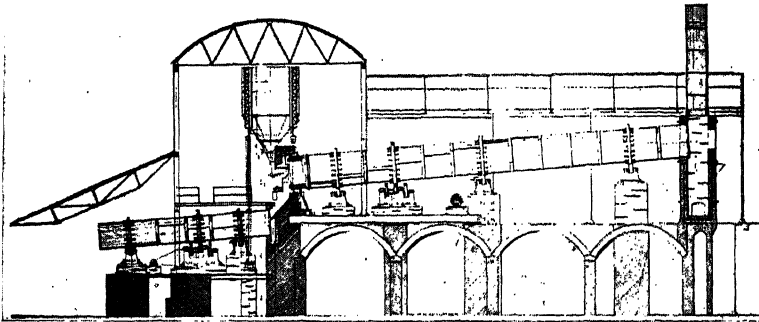


Fig. 67.—Section of Early Rotary Kiln Plant with Cooler below.

the kiln into the cooler (*Figs. 67 and 68*). These coolers are cylindrical tubes similar to rotary kilns, but a good deal smaller in dimensions. The coolers are gear driven, as are the kilns, and the hot end is brick lined, while the lower half is generally lined

with iron plates and is equipped with lifters (*Fig. 70*) which carry the hot clinker up the side of the cooler and cascade it through a current of air which is passing (in an opposite direction to that of the clinker) on its way to provide the air needed for combustion in the kiln.

During the last few years the "integral" cooler has been developed. This is, in its simplest form, an elongation of the kiln and acts as a cooler; when it is in use the pipe carrying the air blast and coal is lengthened to 20 ft. or thereabouts and combustion does not begin until 20 ft. up the kiln, thus permitting the lower portion to be entirely a cooling arrangement. This type of cooler has advantages both in

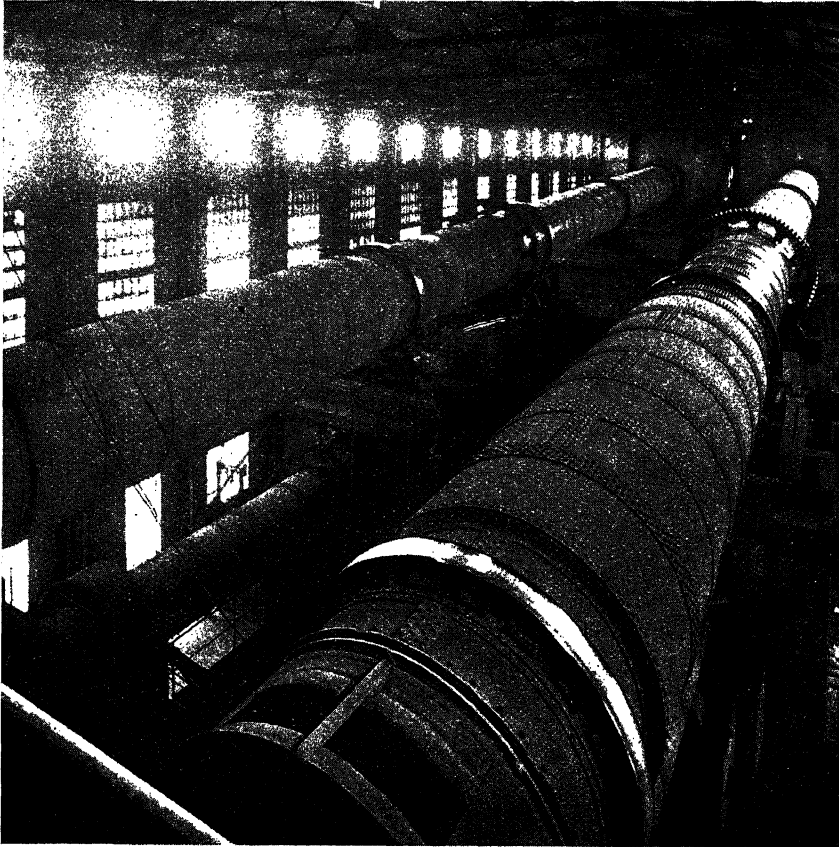


Fig. 68.—Rotary Kilns with Separate Coolers below.

first cost and in efficiency, because it permits the kiln to be erected at ground level instead of being elevated sufficiently to provide for a rotary cooler beneath it. Moreover, the heat radiation losses which occur between the end of a kiln and the end of the cooler through the kiln hood, the clinker chute, and the cooler hood are entirely avoided by the use of the integral cooler. The integral cooler has been developed by some kiln designers in the direction of providing a number of subsidiary tubes for cooling, arranged around the circumference of the kiln shell (*Fig. 71*); it is probable that finality in the design of this type of cooler has not yet been reached, although at the same time it seems likely that the separate cooler will not be embodied in new kilns and is now obsolete.

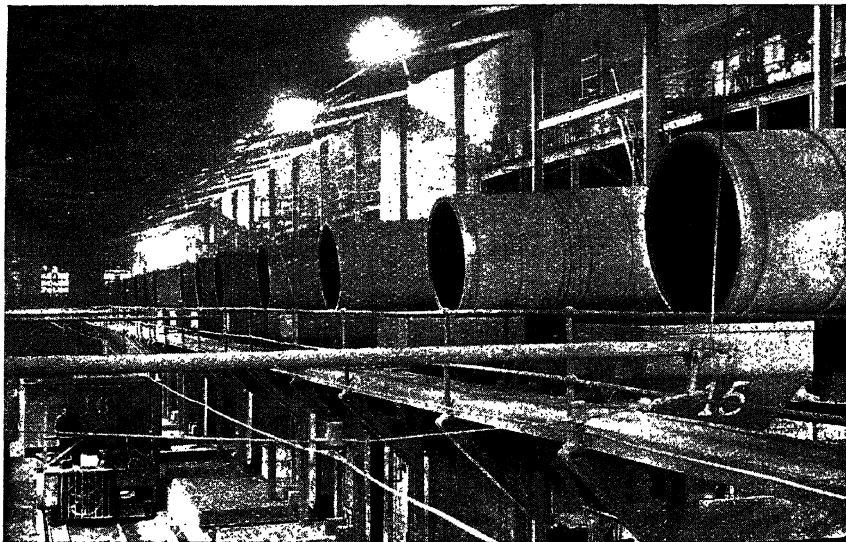


Fig. 69.—Discharge End of Early Type of Clinker Coolers.

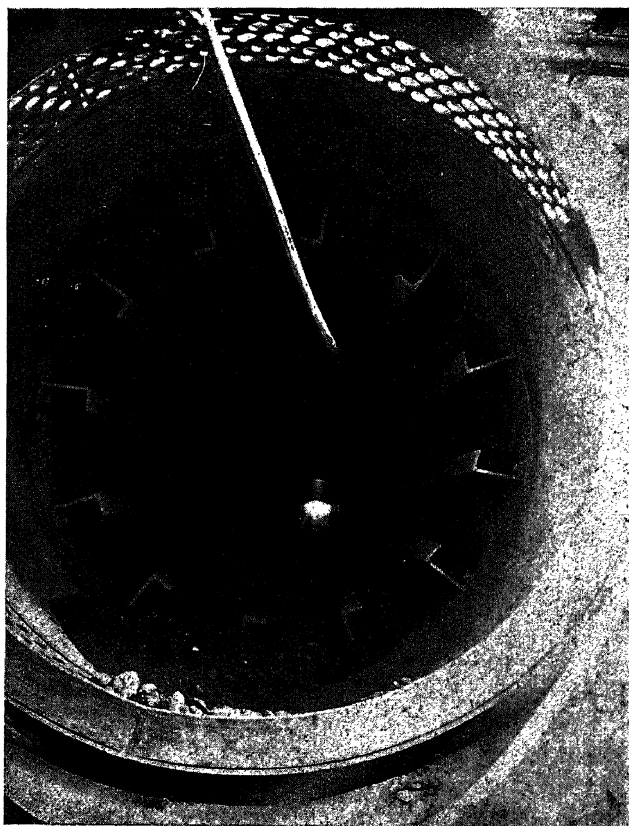


Fig. 70.—Interior View of Rotary Clinker Cooler showing Lifters.

Referring to the separate coolers, there was formerly much discussion as to whether the air required for cooling the clinker should be drawn through the cooler and subsequently into the kiln by the induced draught of the kiln chimney, or whether such air should be forced up the cooler and into the kiln by a fan (*Fig. 72*). The advocates of the latter claimed that it gave better control of the air supply, although it admittedly consumed power which was not used when the chimney alone was relied upon. Induced-draught fans are, however, fitted to many kilns to-day for other reasons discussed later on, and this fact, coupled with the development of the integral cooler, has indirectly disposed of the problem.

The clinker enters the cooler at a temperature of about 2,000 deg. F., and an efficient cooler will deliver it at a temperature at which it can be handled while at

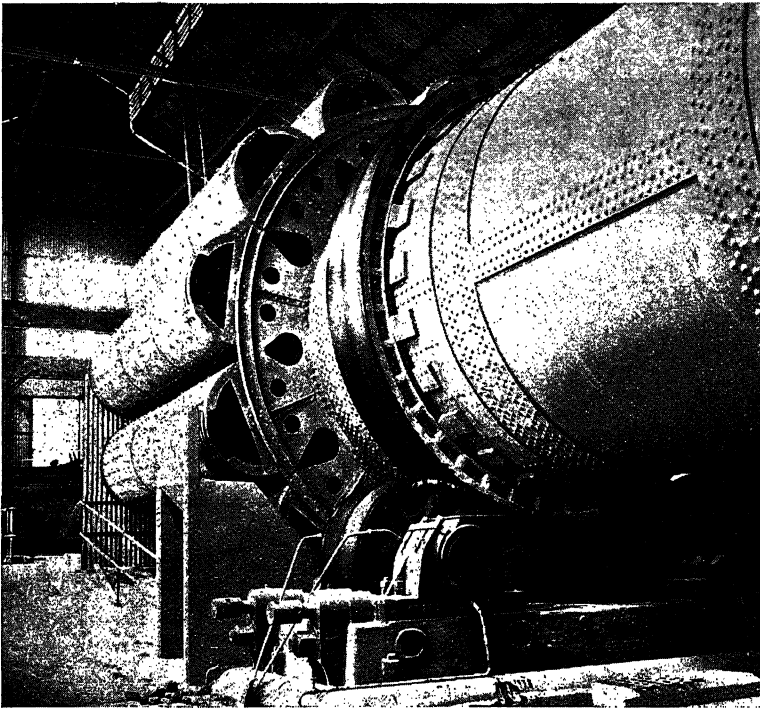


Fig. 71.—Rotary Kiln with “Integral” Cooler.

the same time heating the air for combustion to about 700° deg. F. As the amount of heat in the clinker leaving the kiln is equivalent to about 5 lb. of coal per 100 lb. of clinker, the heat recovery in clinker coolers is of considerable importance.

Rotary kilns as a whole cannot be claimed to be scientifically economical in fuel consumption, because on the wet process from 24 lb. to 26 lb. of coal (dry coal of 12,600 B.T.U.'s per lb.) are consumed per 100 lb. of clinker, and this compares with 15 lb. to 20 lb. of coal consumed in shaft kilns. On the other hand, rotary kilns possess a preponderating advantage in labour cost compared with the shaft kiln, and it is also much easier to produce high-quality cement in the rotary kiln than in the shaft kiln.

Rotary Kiln Lining

The maximum temperature reached in rotary kilns approaches 3,000 deg. F., and this in itself demands a very refractory lining brick, but in addition to this temperature there is mechanical attrition caused by the flow of the clinker over the surface of the brick, and, what is more destructive still, the fluxing action between the basic cement clinker and acid bricks. This fluxing action involves the formation of compounds of lime (derived from the cement) and silica and alumina derived from the firebrick, which melt at a temperature not much over 2,000 deg. F., so that if fluxing is not prevented a firebrick lining (of the acid type) will not endure many days. It therefore became necessary to coat the lining with a layer of cement clinker while the kiln was running, and to train the attendants of the rotary kiln in the practice of this operation. It was discovered that so long as a coating of 2 in. or 3 in. of clinker could be collected on the firebrick lining no further fluxing occurred and

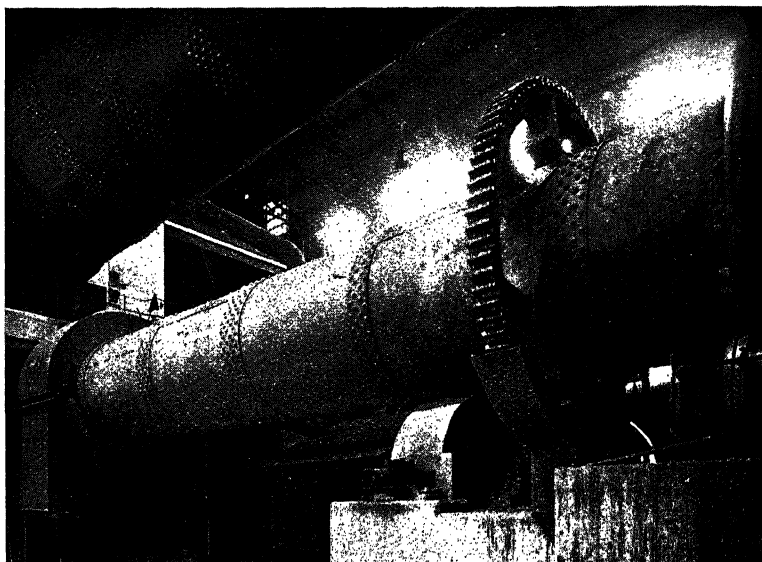


Fig. 72.—Clinker Cooler under Forced Draught.

the kiln could run for a considerable period without renewal of the lining. Each time the kiln cooled down, however, this coating fell off and generally took with it a layer of the firebrick; thus, owing to stoppages associated with mechanical troubles, an average life of the lining in the burning zone was under six months when firebricks of the acid type were employed.

During the last few years bricks containing from 60 per cent. to 70 per cent. of alumina have been employed in the burning-zones, and as such bricks are almost neutral in their chemical characteristics the fluxing action between them and clinker is very small; in consequence, burning-zones lined with aluminous bricks should not require renewal due to wear of the brick in less than twelve months. These aluminous bricks, sometimes known as bauxite bricks, are made from the natural mineral bauxite or other minerals of similar composition, and require very hard burning. Suitable material is not found in England, so that either the raw material or the bricks have to be imported, and this, in conjunction with the

high degree of burning, renders them considerably more expensive than English firebricks, although experience has shown that the higher cost is fully justified by the longer life of the bricks in practice.

Magnesite bricks, composed very largely of magnesia, were also tried in the earlier days of the rotary kiln, but were not extensively adopted owing to their high price and a tendency to spall which decreased their life.

The need for special bricks is confined to the burning zone only, say, one-quarter of the total length of the kiln; the remaining three-quarters of the length can well be lined with ordinary firebricks, because the temperature is not high enough in the upper parts of the kiln to attack the refractory nature of such bricks or to cause fluxing. The upper end of the kiln, which contains nothing more than wet or partially dried slurry, is sometimes lined with ordinary bricks or even concrete placed in situ.

TABLE VIII.—ANALYSES OF BLOCKS USED FOR LINING ROTARY KILNS IN THE BRITISH ISLES.

	Dynamidon	Alite	Alumanite	Curtis	Alosil	Nettle	Williamson Cliff	Parry	Adamantine
Silica (SiO_2) . . .	18.9	21.9	28.6	26.5	36.0	51.3	80.0	63.9	72.6
Alumina (Al_2O_3) . . .	73.2	68.7	64.4	65.0	60.0	43.7	14.0	30.0	22.9
Ferric Oxide (Fe_2O_3) . . .	3.9	4.9	2.1	4.9	1.4	2.6	2.0	4.2	2.5
Lime (CaO) . . .	0.5	0.8	0.1	0.6	0.3	0.4	N.D.	0.2	0.4
Magnesia (MgO) . . .	0.1	0.3	0.5	0.2	0.2	0.6	N.D.	0.2	1.0
Titanic oxide (TiO_2) . . .	3.2	2.1	2.3	1.9	1.6	1.5	2.3	0.1	N.D.
Alkalis . . .	N.D.	1.2	1.5	N.D.	1.0	trace	N.D.	N.D.	N.D.

Coal Firing

As previously mentioned, the kiln is heated by a flame produced by the ignition of finely-powdered coal. A fan is arranged near the hot end of the kiln to blow through a blast pipe of about 9-in. diameter, and into this pipe is fed the coal necessary for the heating (*Fig. 73*). The mixture of coal and air ignites shortly after leaving the pipe and forms a high-temperature flame. In some cases the coal-firing fan is

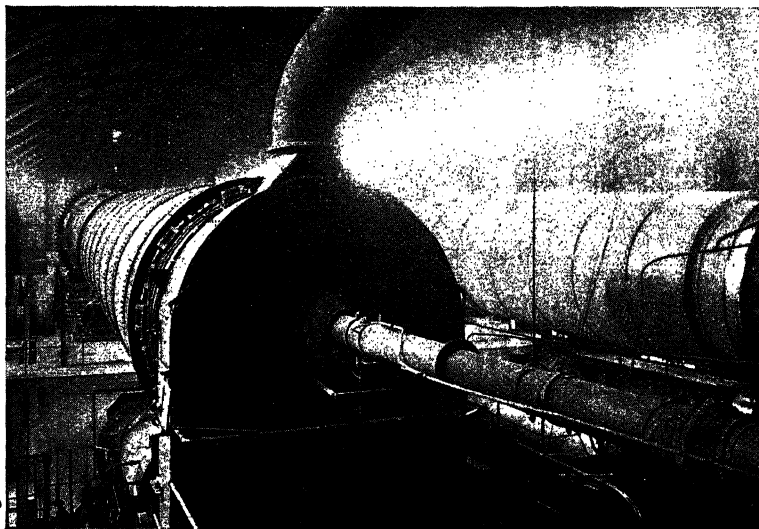


Fig. 73.—Firing End of Kiln, showing Coal Feed Pipe.

arranged to draw hot air from the clinker cooler ; the mixture of hot air and coal thus entering the kiln ignites more quickly than would a mixture of cold air and coal and provides a hotter flame, while at the same time it utilises some of the heat from the cooling clinker. In other cases the coal-firing fan draws its supply of air from the coal mill or coal dryer, and this performs the necessary ventilation of these machines. In more modern practice, as described later, the use of a separate coal dryer is obsolete.

The Coal Mill

For a powdered-coal flame to ignite quickly, as is required in a rotary kiln, it is necessary for the coal to be dry and finely ground, and this implies grinding,

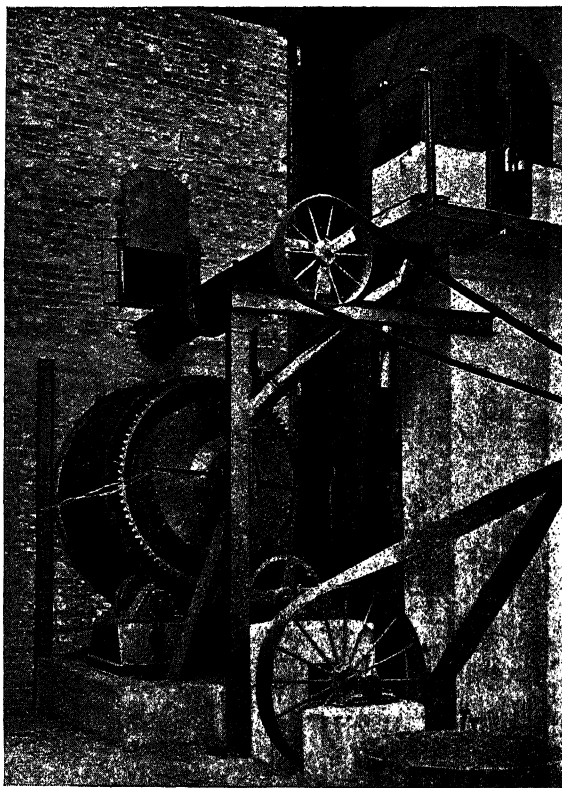


Fig. 74.—Feed End of Rotary Coal Dryer.

and if necessary drying, coal as it is received from the colliery. Only a few years ago coal dryers were considered necessary, and these usually took the form of rotating drums 40 ft. long by 4 ft. diameter and upwards through which the coal was passed. Hot air from the clinker cooler, or hot flue-gases from a specially arranged furnace, passed outside the drum (which was housed in a brickwork chamber) and then through the middle of the drum (*Fig. 74*), and the steam from the coal either went to the atmosphere or was drawn into the kiln by the coal-firing fan. Owing to the necessity of avoiding the temperatures in the coal-drying drum getting sufficiently high to ignite the coal, coal drying by this means was a somewhat inefficient process, and the evaporation of water per pound of coal rarely exceeded 2 lb. From the

drying drum the coal was passed to grinding mills, which were either of the tube-mill variety described in connection with clinker grinding, or of the pendulum variety. From the coal mills the fine powder passed to silos or hoppers before being fed into the kiln.

Self-contained single-unit dryers and pulverisers or grinding machines are popular. These machines take small coal as delivered (without drying) and pulverise it and inject it into the rotary kiln, so that they perform the functions of the coal dryer, coal mill, and coal-firing fan which were necessary in the earlier installations. These pulverisers sometimes take the form of high-speed disintegrators with disks revolving on a horizontal spindle, while in other cases a combination of a small ball mill or tube mill and a cyclone separator is adopted. In both cases it is necessary for hot air from the clinker cooler to be drawn through the mills to facilitate the grinding of wet coal. When a cyclone is used the bulk of the powdered coal is separated and can be collected in a hopper for storage. These machines have their limitations when dealing with coal containing more than 10 per cent. of moisture, and are not so well adapted for fine grinding when using certain classes of fuel, but their advantages are such that they are now generally adopted.

Quality of Coal

In a certain sense it is true to say that almost any quality of coal can be used provided proper treatment is given to the coal before injection into the kilns. Generally speaking, however, the ideal coal for cement burning in rotary kilns, when cost is considered in conjunction with quality, would be one containing less than 5 per cent. of moisture, no more than 10 per cent. of ash, and with a minimum of 20 per cent. of volatile matter. Such a coal could be successfully used if ground to a residue of about 20 per cent. on the 170-mesh sieve. There are cases, however, of the residue exceeding 30 per cent. on the 170-mesh sieve with successful results, although in these cases the ash from the coarsely-ground coal may tend to collect in one region of the kiln and form clinker rings, and there may not be the rapidity of ignition which is valuable for heat efficiency. It would, however, be possible to use coal containing less than 20 per cent. of volatile matter provided the fineness of grinding had been carried to the necessary degree to permit of quick ignition, and at some works the residue on the 170-mesh sieve is as low as 5 per cent. It is a matter for consideration whether the power expended in such fine grinding is counter-balanced by the cheapness of the coal containing a low proportion of volatile matter. The percentage of ash in coal used in rotary kilns may, and does, vary over a considerable range, and rotary kilns have with success on occasions been fired with coal containing 25 per cent. of ash. It has to be realised, however, that much of the ash in the coal mingles with the cement raw materials and alters the chemical composition of the latter, so that it is necessary for the chemist to adjust the chemical composition of the raw materials to meet the change in composition arising from admixture with coal ash.

Slurry Lifters

Mention has been made of slurry lifters inside the feed end for the purpose of spreading the raw materials and getting more intimate contact between them and the hot gases passing up the kiln. In the wet process, unless an attempt is made to distribute the raw materials in this way by means of lifters or other devices, the gases leaving the kiln may reach a temperature of 900 deg. F., or even more, and this

involves very considerable waste of heat. Hence a considerable amount of investigation has been done upon lifters of various designs for the purpose of distributing the slurry and causing intimate contact between it and the hot gases.

These lifters take the form of buckets attached to the inside of the kiln shell, or of star-shaped diaphragms occupying the cross-section of the kiln at the

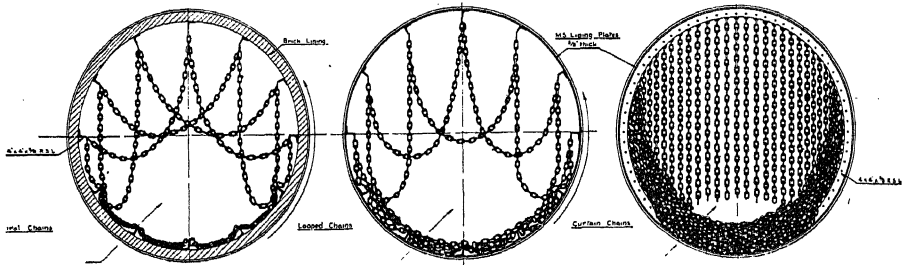


Fig. 75.—Methods of Hanging Kiln Chains.

slurry end, or of a single concentric tube or nests of tubes, or in recent years of curtains or festoons of chains (*Figs. 75-77*) loosely suspended in the interior of the kiln. The type of slurry lifter employed has to be suitable for the nature of the slurry. With viscous slurries the lifter has to be of a very simple type, otherwise

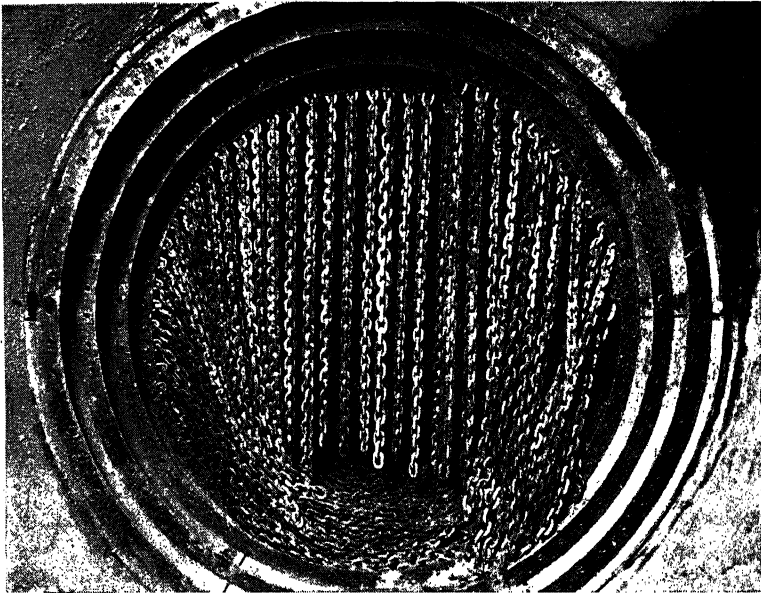


Fig. 76.—Setting of Chain Curtains in Kiln.

there is danger of the formation of accumulations of slurry "pug," which obstruct the draught through the kiln, while with more friable slurries more complicated lifters can be employed.

Well-designed slurry lifters are successful in keeping the temperature of the gases leaving the kiln down to about 400 deg. F. It will be realised that the installa-

tion of slurry lifters forms some obstruction to the passage of the hot gases through the kiln, and where the lifter system is complicated a fan will be needed to assist the gases in their passage through such system.

Scientific Control of the Rotary Kiln

Although the rotary kiln has been used in this country for forty years there is still no general agreement on the technique of the burning operation. The nature of the flame employed can be varied very considerably by modifications of the burner pipe and its position, and of the proportions between the air entering the kiln through the burner pipe and the secondary air entering up the clinker chute. There are probably several ways of attaining the same end, but there is a notable improvement in the heat efficiency of rotary kilns to-day compared with those of a few years ago. As a result kilns are now designed for a maximum coal consumption of 24 per cent. based on clinker output with slurry containing not more than 40 per cent. of water, as compared with, say, 29 per cent. of coal and more with old type kilns.

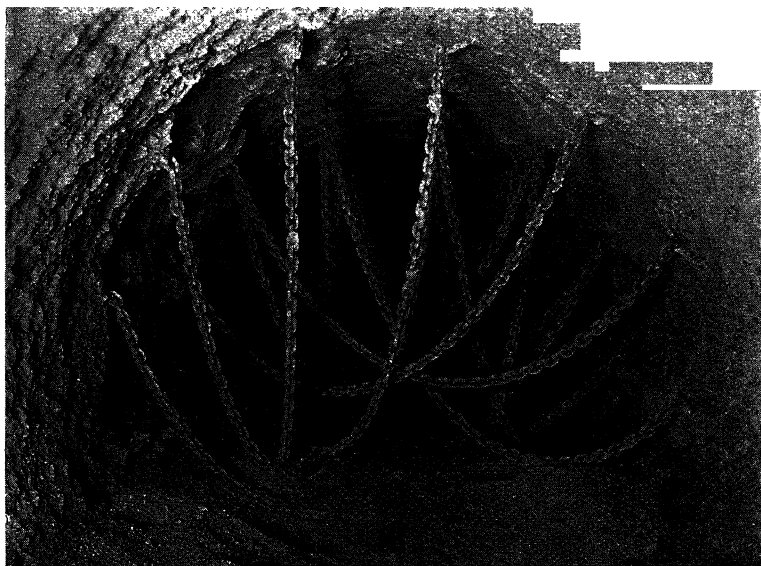


Fig. 77.—Interior of Rotary Kiln Fitted with Chain Lifters.

In the initial stages of rotary kiln development the control was on a rule-of-thumb basis, but of late years scientific control of combustion has been introduced with considerable advantage to economy. It can now be claimed that in no industry is coal burnt with such perfect combustion as in well-controlled rotary cement kilns, because such kilns will issue the products of combustion with practically no excess of air and with no unconsumed coal. To obtain such perfect combustion it is necessary to have constant analyses of the gases leaving the rotary kiln, and this is done by electrical instruments which take samples of the gas and record continuously the proportions of CO_2 , oxygen, and CO . This enables the chemist to detect at once any imperfect combustion, which can be remedied by adjustment of the air supply.

Even in the best rotary kilns in use there is a considerable loss of heat owing to the high temperature of the gases leaving the kiln, and a continuous temperature

recorder is needed so that any avoidable waste can be prevented. A well-designed kiln will issue its gases at a temperature below 400 deg. F., while in some of the older kilns this temperature used to reach 900 deg. F. and thus involve a loss of about five tons of coal per 100 tons of clinker when compared with the more efficient rotary kiln.

Another important item in heat efficiency is the control of the air supply, to ensure that as much as possible of the air required for combustion is previously heated by the clinker leaving the kiln, and control of this department demands the use of draught gauges to indicate the air flow. The aim of the kiln controller is to have a perfectly even feed of raw material and a perfectly even flow of coal and air into the kiln, so that no adjustments are needed and the output of perfectly burned clinker at constant rate can be obtained. This ideal is, however, not attainable in practice owing to variations in the rate of flow of material down the kiln and to variations in quality of the coal. Hence it becomes necessary to have facilities for adjustment; this can be done both with the rate of flow of raw material and the quality of coal, or by variation in the speed of the kiln, enabling the flow of material down the kiln to be retarded or accelerated as needed.

The loss of heat occasioned by the high temperature of the chimney gases has already been referred to, and probably the next most important loss is that by radiation from the surfaces of the kiln and the cooler. Such radiation is generally thought to be equivalent to about four tons of coal per 100 tons of clinker. Some attempts to minimise this loss have been made by insulating the shell of the kiln, usually by installing layers of heat-insulating material between the firebrick lining and the steel shell of the kiln. In some cases the heat radiated from the shell of the kiln has been used for coal drying.

Various attempts have been made to improve the thermal efficiency of the rotary kiln, and suggestions have been made for a division of its functions. Among the best known of these inventions is the Lepol kiln, in which a travelling grate is installed behind the kiln. This grate carries a layer of raw mix towards the feed end of the kiln, and the hot gases from the kiln travel over the grate in counter-current and, to ensure maximum contact, are sucked down through the grate and its load of material. The raw mix must be prepared to effect the heat exchange as efficiently as possible, and this kiln includes the formation of small balls or lumps which, because of their minimum contact with one another and their maximum exposure of surface, effect this transfer efficiently. Actually, the lumps lie on the grate in a layer 6 in. to 8 in. thick, and their water content is 12 to 14 per cent., yet the transfer of heat is so effective that the temperature of the gas drops from over 900 deg. C. above the material to about 150 deg. below the grate, while the material reaches the kiln already in large measure decarbonated. The advantages claimed for the process are: (1) Gases from the kiln reach the flue at the minimum of excess temperature; (2) the dust contained in the discharged gas, and therefore lost from the cement feed, is practically nil, as the bottom layers are cooler and still contain some moisture, thereby extracting the dust from the gas in the manner of an absorption filter; (3) the balls or lumps formed for the grate retain their form during the burning, and the vaporisation of their water leaves them porous in structure, so that they are in especially good condition for grinding; (4) the construction and operation of the kiln are greatly simplified, for kilns of 300 ft. or more in length can be replaced by kilns 80 ft. to 100 ft. long, with a greatly lowered loss of heat by radiation. At the same time, it is stated, there is no unfavourable condition added by the requirement of the travelling grate, for the gases cross the grate at such reduced temperatures that the thermal demands on them are not great.

A kiln installation of this type is shown in *Fig. 78*. The raw feed is delivered from a bin (1) by a screw (2) and a bucket-elevator (3) to a small feed-bin (4). From here the material is fed, and at the same time sprinkled with water, into a drum (5), which is rotated to form the raw mix into lumps. These are then collected in a bin (6) which feeds the travelling grate (7) enclosed in a chamber. The material then travels slowly to the kiln (8) and finally passes through the cooler (9). The hot gases pass through these machines in counter-current, being sucked through the grate by a fan (10) and finally passing to the stack (11). Particles falling through the grate are collected in hoppers (12) and returned by screw-conveyors (13) to the elevator. An auxiliary chimney (14) is used only in putting the installation into operation. This type of kiln is at present applicable to the dry process, and a fuel consumption of 16 to 17 tons of coal per 100 tons of clinker is possible.

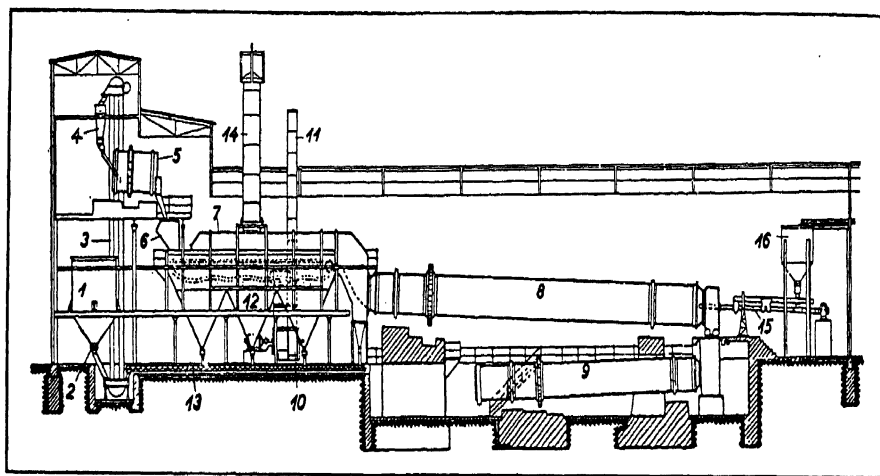


Fig. 78.—Kiln with Travelling Grate.

In Germany the Miag calcinator has been developed. This consists of a rotating drum containing loose iron bodies into which the slurry and hot kiln gases are fed and from which dried slurry emerges in nodules to feed the rotary kiln. The makers guarantee 21.5 per cent. coal (7,000 calories) consumption with slurry containing 40 per cent. water.

Other ideas and inventions are now being developed with a similar object, i.e. to reduce the temperature of the waste gases and effect fuel economy. The author feels, however, that sufficient practical experience is not yet available in regard to many of these, although most of the new ideas for fuel economy with the rotary kiln are being well tried out in practice. This brief summary, however, of rotary kiln economics and practice shows that the details of burning plants have to be settled with the same care that is given to the selection of raw materials and the site of the works.

CHAPTER X

CONTROL OF ROTARY KILNS

THE production of cement clinker in a rotary kiln, from raw materials prepared by either the wet or dry process, combines four stages of the process in one apparatus. These stages are

- (1) Drying the raw material (in the so-called dry process the prepared raw material enters the kiln in a slightly damp condition).
- (2) Heating the raw material to the temperature at which carbon dioxide is driven off.
- (3) Further heating the material until all the carbon dioxide is driven off with the formation of calcium oxide.
- (4) Raising the temperature of the calcium oxide in the presence of the argillaceous constituents of the mix to the point when incipient fusion takes place.

Scientific control of the burning operation has a marked effect on efficiency and economy. There are many points at which it would be desirable to measure the temperature or other factors concerned in this series of operations, but practical difficulties have up to the present limited the possibilities of such measurements. Owing to the form of construction of a rotary kiln and the nature of the material dealt with, it is difficult to use scientific instruments for observing and controlling the second and third stages of the process. It has therefore been necessary in practice to confine attention to the relatively cool end where the raw material is fed in and the hot end where combustion of the fuel and incipient fusion of the materials take place and the clinker passes out.

Dealing first with the cool end, the observations and measurements which are desirable are

- (1) Temperature of the exit gases.
- (2) Composition of the exit gases.
- (3) Quantity of the raw material fed into the kiln.
- (4) Percentage of moisture in the raw materials.
- (5) Quantity of dry raw materials carried away with the exit gases.
- (6) The draught in the back-end due to chimney or fan.

At the hot end instruments may be usefully employed for measuring the

- (1) Temperature of the clinker in the zone where incipient fusion takes place.
- (2) Pressure of the air in the kiln hood and firing pipe.
- (3) Weight and rate of feed of fuel, whether pulverised coal or oil.
- (4) Quantity of primary air used for conveying the pulverised coal into the burning zone.
- (5) Temperature of the clinker leaving the cooler.
- (6) Temperature of the kiln and cooler shells.
- (7) Weight of clinker produced.

It is proposed to deal in some detail with the instruments available for these purposes.

Temperature Measurements

The temperature of the exit gases varies from 400 deg. F. or less in the modern wet-process kiln to 1,200 deg. F. or more in a dry-process kiln. For ascertaining the lower range of temperature it is possible to use a nitrogen-filled mercury thermometer or vapour-tension thermometer. These instruments are liable to be damaged if heated beyond the maximum temperature for which they are calibrated. For the higher range of temperature another means of measurement is essential, and experience has shown that it is better to use for the lower range also an instrument which will stand up better to the excesses of temperature and the arduous conditions imposed by rotary kiln practice.

The thermo-electric pyrometer can be made to stand up satisfactorily to the heavy duties which industrial conditions impose, and it has been extensively adopted in the cement industry. A pyrometer equipment consists of a thermo-couple and an indicator or recorder, operated by the electrical energy produced when the thermo-couple is heated. The thermo-couple consists of two strips of dissimilar metals or alloys which, when brought into intimate contact at a point and heated, produce a difference of electrical potential at the other extremities of the strips. When a galvanometer or millivoltmeter is placed in circuit across the cool end of the two metals composing the couple, an electric current will flow and cause the needle of the instrument to be deflected. The amount of deflection will depend entirely on the temperature difference between the hot and cold ends of the couple, as the greater the difference the higher is the electromotive force and therefore the current which will flow. The electromotive force set up by this means may be anything up to 60 millivolts, depending on the temperature and the metals used for the couple. It is usual for the galvanometer or millivoltmeter to be calibrated so as to read direct in degrees of temperature. This is the simplest form of thermo-electric pyrometer, but in practice it is necessary to add many refinements before a reliable and robust equipment is available.

The thermo-couple may be constructed of many different pairs of metals or alloys, and these group themselves into two classes, namely, those constructed of rare metals (as platinum, iridium, rhodium, etc.), and those in which are used the base or cheaper materials such as iron, copper, chromium, and nickel. For many industrial purposes, particularly cement works use, couples constructed of base metals are employed, the usual combination being iron and a copper alloy known as constantan. The couple usually takes the form of a tube about $\frac{3}{8}$ in. diameter made of iron with a constantan wire running through the centre and welded into one end of the tube to seal it. At the other end, which is the cool end, the tube and constantan wire are brought out to separate terminals mounted on an insulated head. The insulating material should preferably not be of porcelain or other brittle material liable to break if the thermo-couple is dropped. The constantan wire must be prevented from touching the tube between the thermo-junction and the head, and insulating beads, porcelain tubes, or asbestos are used to prevent this when the wire is not still enough to do so.

It is not proposed to deal here at great length with all the technical details and refinements which are embodied in the modern thermo-couple, but the following is a short description of the principle involved. In the simple form of pyrometer already described changes of temperature at the hot end result in changes of temperature at the cool end. The measuring instrument is also affected by changes of temperature, as the conditions are rarely similar to those under which it was

calibrated. Variations in temperature such as these would upset the calibration of the equipment owing to changes in the electrical resistances of the circuit, and to overcome this difficulty it is necessary to place in series with the instrument a ballast resistance of high value so that in comparison the changes in resistance due to external causes are small. At the cold junction the difficulties due to change of temperature are overcome by means of a compensating extension. This takes the form of a cable, the conductors of which are made of metals thermo-electrically interchangeable with the couple, connected in series with and between the couple and instrument. The effect of this is to remove the cold junction to a point where it will not be affected by changes of temperature at the hot end of the thermo-couple. The leads of the compensating extension may be taken right up to the measuring

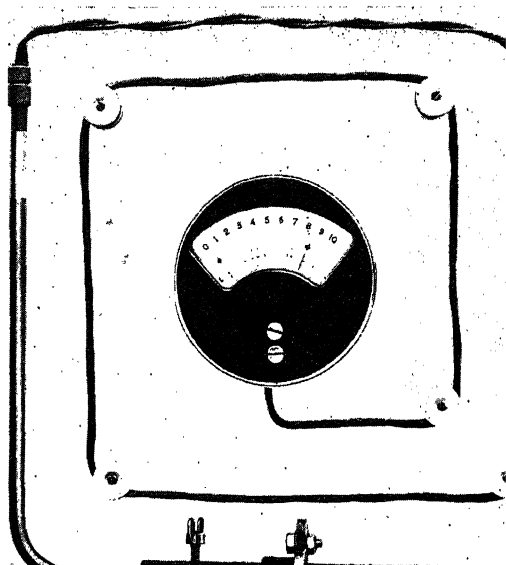


Fig. 79.—Indicating Pyrometer.

instrument, but more usually, particularly where the distance is considerable, copper leads are used between the end of the compensating extension and the instrument. The length of the leads may be anything in reason, and frequently in a cement works are as long as half a mile. *Fig. 79* shows the component parts of an indicating pyrometer consisting of sheathed stem, compensating extension copper leads, and indicator.

One advantage of the thermo-electric pyrometer over the gas-filled mercury thermometer and other modifications of the mercury-in-glass or steel thermometer, or vapour-tension thermometer, is that having once converted changes of temperature at one point to changes in electrical potential at another and distant point it is possible to place the indicating or recording instruments in almost any position. The usual arrangement of a thermo-electric pyrometer equipment in a cement works includes an indicating instrument on the firing floor of the kiln for the use

of the operator, and a recording instrument in either the manager's or foreman's office. A single-point recorder with circular chart is illustrated in *Fig. 80*.

There are generally other temperatures than the exit-gas temperature which require measurement. In such cases it is usual to provide a multi-point switch which enables the operator to select the temperature point desired. The recorders are supplied with up to four readings on one chart, different coloured inks being employed to distinguish the several points of temperature measurement. Where more than four points are to be recorded at the same time it is usual to have additional

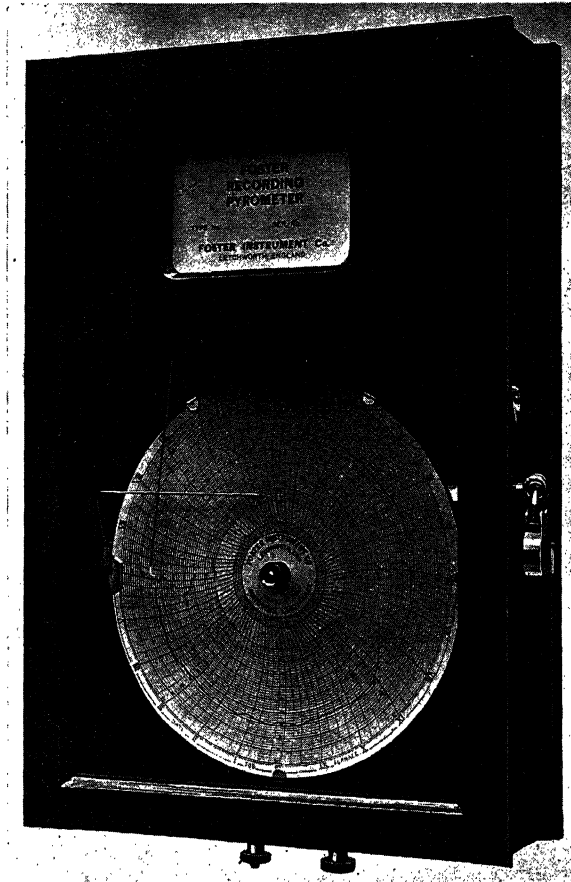


Fig. 80.—Recording Pyrometer.

recorders, but if only four records are required of an equipment with more than four points, then a plug-type switchboard can be used. This allows any one of the four ways on the recorder to be connected to any circuit. A typical instrument of this type is shown in *Fig. 81*. *Fig. 82* shows a two-point strip type chart recording pyrometer and *Fig. 83* a recorder with two charts for three records each.

In the selection of the most suitable position and method of arranging the various parts of the pyrometer equipment, where possible the couple should be placed so that it hangs vertically, but if a horizontal position has to be selected a

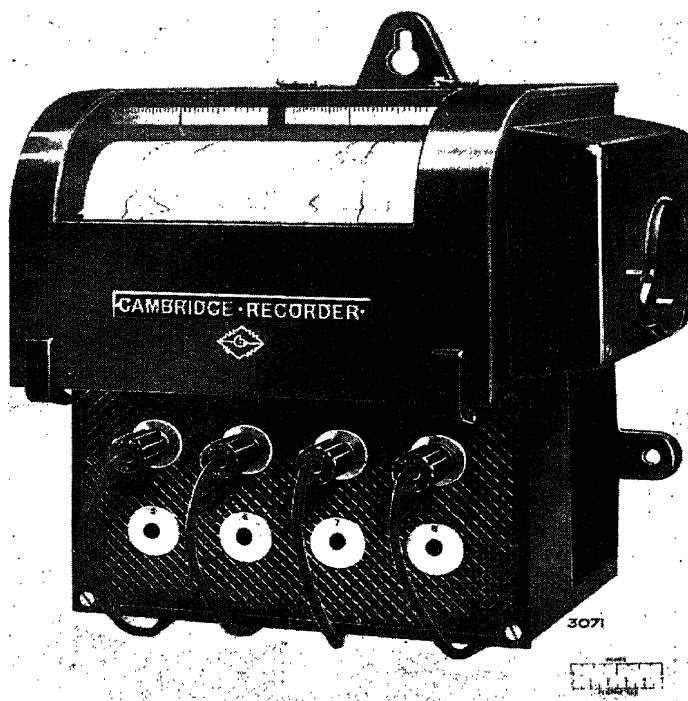


Fig. 81.—Multi-point Recording Pyrometer.

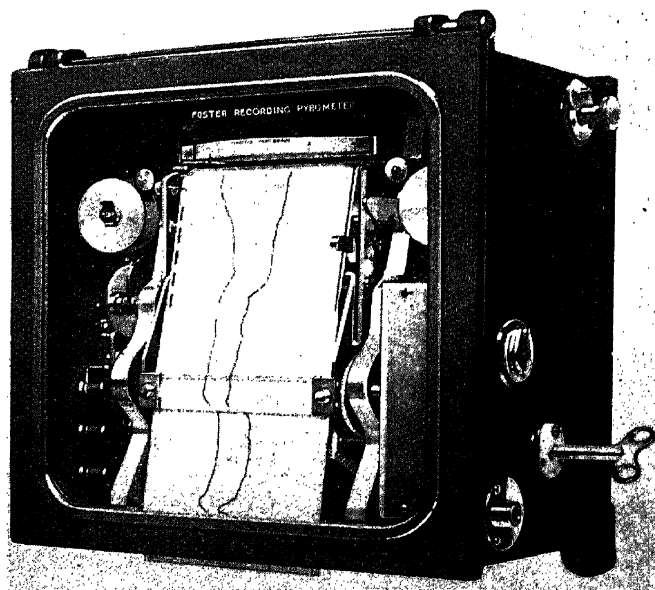


Fig. 82.—Two-point Recording Pyrometer.

supporting tube should be arranged to come within about 12 in. of the hot end. In practice it is difficult to select a position which will give the average temperature of the gases it is required to measure. In the back end of the kiln there is considerable turbulence of the gases, and to find the point of average temperature it is necessary to take a number of readings in both the vertical and horizontal planes in the path of the gases and to plot the temperature distribution. Care has to be exercised to avoid placing the end of the couple where it can lose heat by radiation or conduction to a near object, such as the slurry feed-pipe to the kiln. The proximity of a relatively cool object may sometimes account for a temperature reading lower than the real temperature. The end of the couple must be frequently cleaned of any deposit of slurry or dust, as these will cause the temperature indications to be incorrect. The cables connecting the couple to the instrument should be properly insulated and

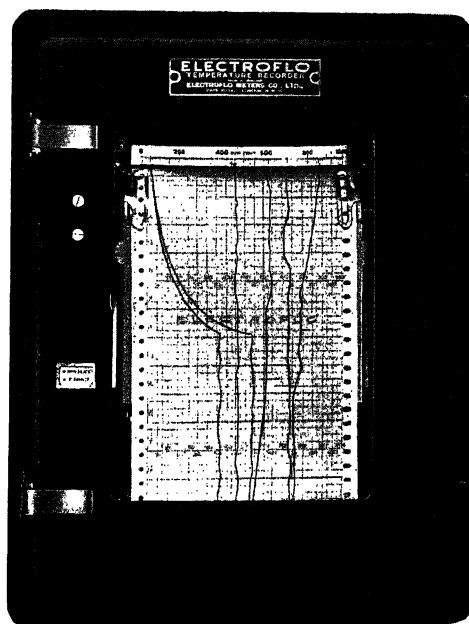


Fig. 83.—Two-Chart Three-point Recording Pyrometer.

secured, and as far as possible they should be placed where radiation from the kiln cannot affect them.

Where there is a number of points to be measured it is usual for the cold junctions to be immersed in an oil bath, means being provided for measuring the temperature of the oil and of protecting it from changes of temperature due to external causes. Such an arrangement ensures that the cold junctions of all the cables are at the same temperature and that the temperature readings are strictly comparable. *Fig. 84* shows an oil-immersed cold junction with indicating pyrometer and six-way switch. The rigid method of mounting the equipment and the enclosing of the circuit leads in galvanised conduit should be noted. The mounting of the instrument, whether indicator or recorder, requires careful thought. The site selected should be as cool as possible, and the instruments, if mounted near the kiln, must be protected from radiated heat. It is also essential that the position be as free from dust as is

practicable, as, although most of the commercial instruments are enclosed in cases, it is rarely that they keep out the finest dust.

Exit-Gas Analyses

The exit gases consist mainly of nitrogen, carbon dioxide, moisture in the form of superheated steam, some free oxygen, and sometimes a trace of carbon monoxide. There are many types of instruments available for determining the percentage by volume of the constituent gases. Where a complete analysis is required it is usual to use an Orsat apparatus, of which there are several types. Where partial analysis

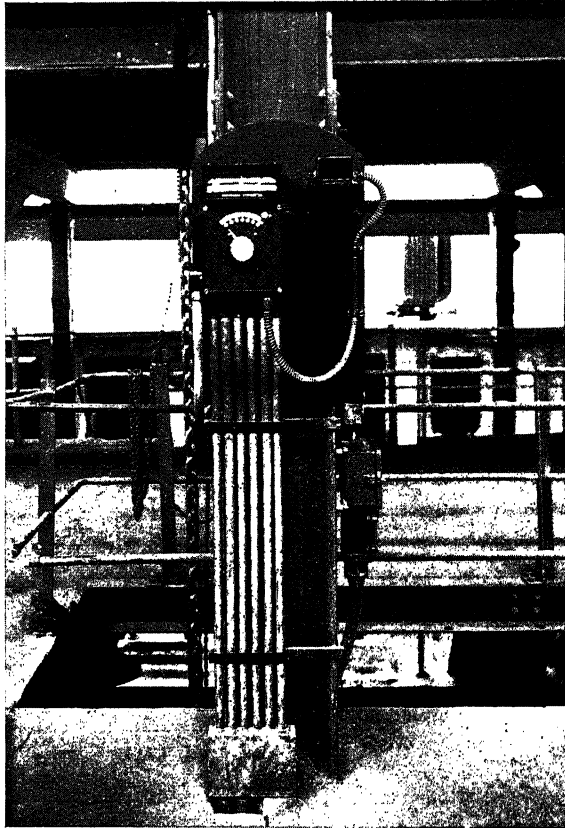


Fig. 84.—Indicating Pyrometer and Six-way Switch.

is required, recording instruments, usually for carbon dioxide only, but in some cases also for oxygen or for carbon monoxide, may be used.

The Orsat apparatus consists of an aspirator, water-jacketted measuring burette, and absorption pipettes. The burette is generally calibrated to read in tenths of a cubic centimetre and has a total content of one hundred cubic centimetres. For aspirating purposes water is generally used. The pipettes are arranged for determining the percentages by volume of carbon dioxide, oxygen, and carbon monoxide, the nitrogen being determined by difference. As the temperature at which the analysis is made is about atmospheric, the steam in the gases is condensed and for all practical purposes may be neglected.

For the absorption of carbon dioxide a solution of potassium hydrate or sodium hydrate may be used; the former is generally preferable. An alkaline solution of pyrogalllic acid may be used for oxygen, and either an acid solution of cuprous chloride or an ammoniacal solution of cuprous chloride may be used for carbon monoxide. The latter has greater absorbing power and is therefore preferable.

The absorption of carbon dioxide is readily carried out in the simplest form of pipette, but oxygen and carbon monoxide are not so easily absorbed. In order to shorten the period of absorption as much as possible various forms of pipette have been devised which either cause the gas to come in contact with as large a surface of the absorbing solution as possible or make the gas pass through the absorbent in a state of turbulence. In the simplest form of pipette, shown in *Fig. 85*, the gases pass by means of the central tube to the bottom of the pipette and then bubble up

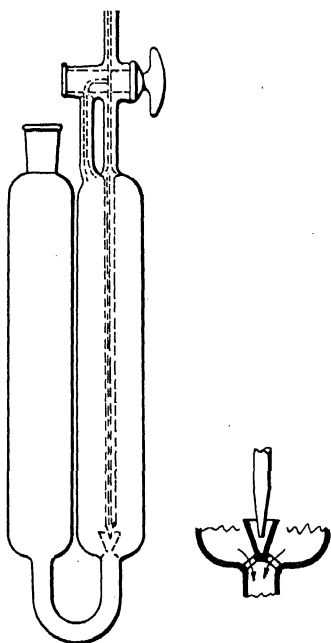


Fig. 85.—Absorption Pipette.

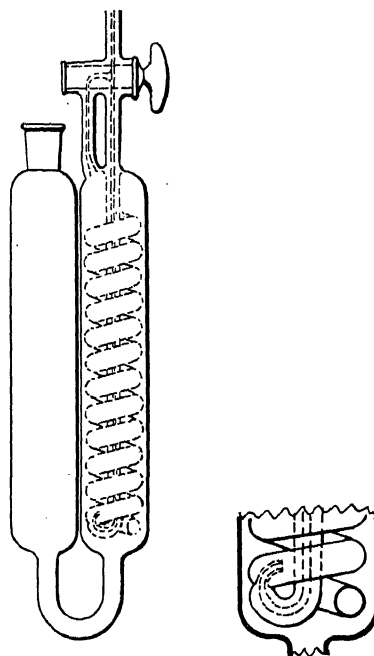


Fig. 86.—Rapid Absorption Pipette.

through the absorbent. The same type of pipette is sometimes fitted with a number of small glass tubes. This considerably increases the surface wetted with the absorbent with which the gas comes in contact. *Fig. 86* shows a pipette in which the absorption takes place very quickly and is effective in determining traces of oxygen or carbon monoxide. Its efficiency is due to the fact that the gas and the absorbent are brought together in a state of turbulence. The gases pass down through the central tube as in the type already described, but the bottom end of this tube is bent upwards and tapers into a spiral of large diameter which reaches nearly to the top of the enclosing vessel. A portion of the centre tube at the point of intersection with the spiral is continued upwards inside the spiral and finishes in the form of a jet. The gases issuing from the jet therefore act as in an injector and draw up with them a quantity of the reagent which enters through the open end of the bottom of the spiral. The gases and reagent pass up together through the spiral to the top

of the pipette. Considerable agitation takes place, and the gases and reagent are brought into intimate contact in their passage through the spiral, resulting in the quick absorption of the gas. A complete portable Orsat apparatus is shown in

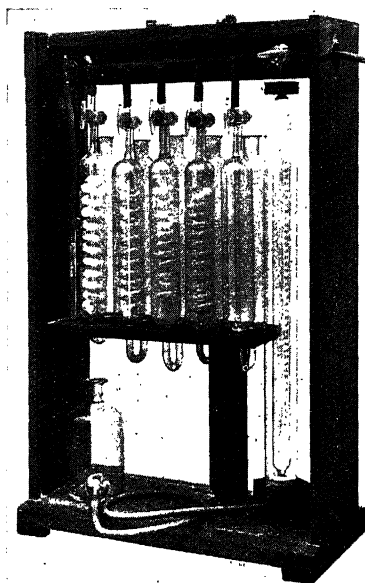


Fig. 87.—Portable Orsat Apparatus.

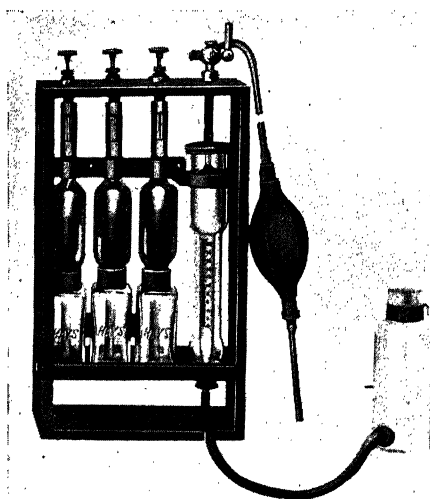


Fig. 88.—Orsat Apparatus with Metal Parts.

Fig. 87. The apparatus may also be used for determining the presence of certain hydrocarbons, also, when used in conjunction with a Hempel bomb, for hydrogen and methane, but these gases are not present in cement kiln gases. It is also made with many of the glass parts replaced by metal parts (*Fig. 88*), but the principle

and method of determining the constituent gases are exactly the same as already described.

When a continuous record of the analysis of certain of the constituent gases is desired there are several satisfactory recording instruments available, but it is necessary to confine the analysis to not more than two of the gases. Many of the recording instruments depend on absorption, but a few employ other principles.

One instrument for recording the presence of carbon dioxide is electrically operated and depends on the difference in thermal conductivity between carbon

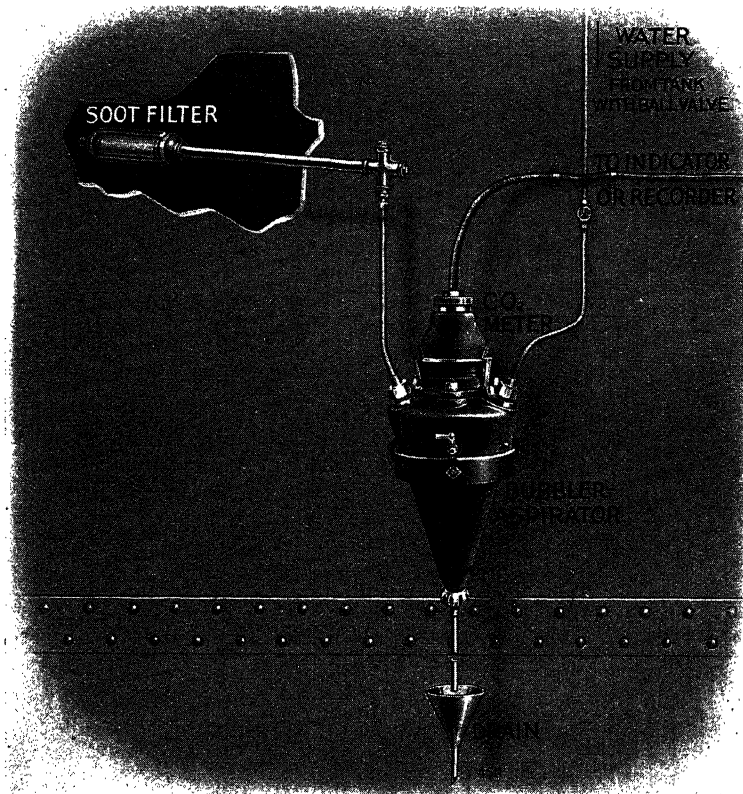


Fig. 89.—Electrically-operated CO₂ Meter.

dioxide and air. The complete equipment (*Fig. 89*) consists of soot filter, water-operated aspirator, and CO₂ meter. The CO₂ element, named the katharometer (*Fig. 90*), consists of two cells each containing identical spirals of platinum wire which are electrically connected so as to form two arms of a Wheatstone bridge. The cells are enclosed in a metal casing. When an electric current is passed through the spirals they become heated and lose heat to the casing enclosing the cells. Their temperature, and therefore their electrical resistance, will be changed depending on the thermal conductivity of the gases surrounding them. If air be passed through both the cells at the same rate of flow the relative resistance of each spiral remains

unchanged. When, however, air is passed through one and carbon dioxide through the other a greater cooling effect is produced in one cell than in the other; one leg of the Wheatstone bridge is thrown out of balance, resulting in deflection of the galvanometer which is in circuit, the extent of the deflection being dependent on the amount of carbon dioxide present. The galvanometer is calibrated in percentage of carbon dioxide. The katharometer, which should be be placed as near as possible to the point at which the gas is to be sampled, has the gas and air induced through it by means of an aspirator. Either indicating or recording instruments, or both, may be used, and these can be placed at any reasonable distance from the katharo-

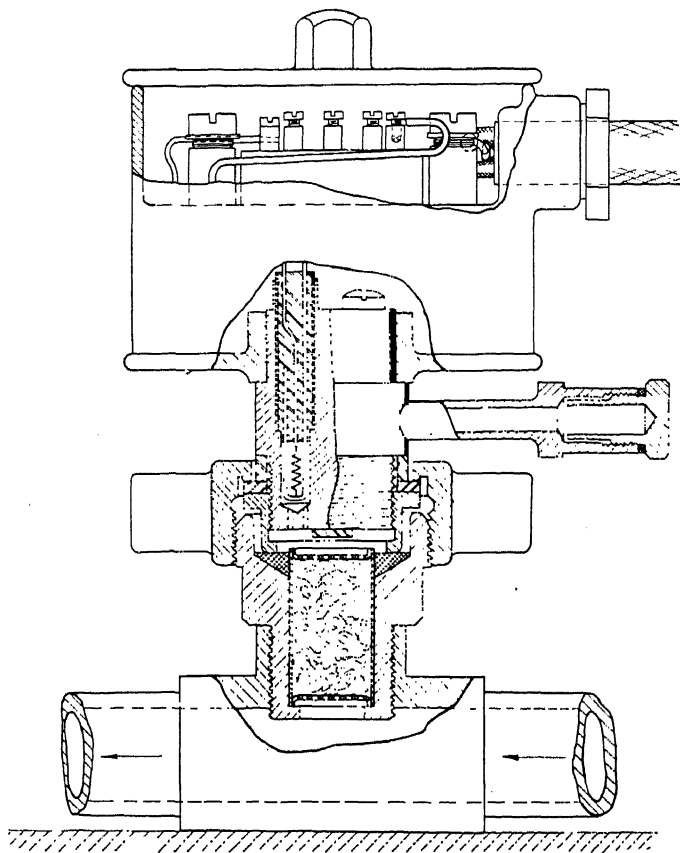


Fig. 90.—Katharometer.

meter, as the only connection between them is some insulated wires. These instruments are generally similar to those used for pyrometry.

The electrical method in slightly modified form is also used for determining the percentage of carbon monoxide or oxygen, but in both cases the determination is by difference as the gas is converted to carbon dioxide by combustion and the difference in carbon dioxide before and after combustion is ascertained.

The Arkon recorder is made for showing the presence of either carbon dioxide alone or carbon dioxide and oxygen. This instrument works by absorption, caustic potash being used as the reagent for carbon dioxide and stick phosphorus for the oxygen. The readings obtained are therefore direct, and not by difference. The

aspirator, which may be operated either by water or electrical means, is usually adjusted to give about thirty readings per hour.

The combined carbon dioxide and oxygen recorder (*Fig. 91*) is made for showing various percentages of both the gases, but the standard range for oxygen is rather high for rotary kiln gases and in consequence it is very difficult to read small differences in the oxygen content.

The W.R. recorder for carbon dioxide also works on the absorption principle,

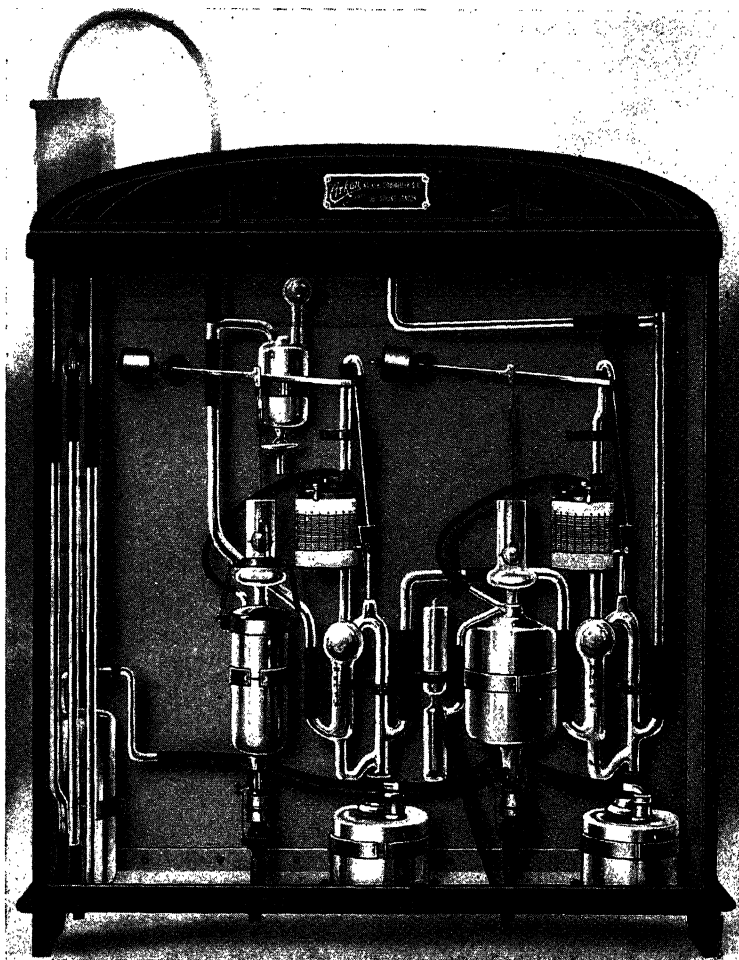


Fig. 91.—Combined Carbon Dioxide and Oxygen Recorder.

but unlike many of this type the indication is continuous. *Fig. 92* shows diagrammatically the arrangement for indicator only, and *Fig. 93* is a view of an instrument for indicating and recording. The absorption part of the instrument consists of an outer and inner vessel, the latter being a porous pot which contains the absorbing reagent in the form of a cartridge. One tube of a water column gauge is connected to the outer vessel and the second to the inner vessel. The gases containing the carbon dioxide are aspirated through the outer vessel by the usual means. Some of these gases pass through the porous pot, where the carbon dioxide is absorbed by the

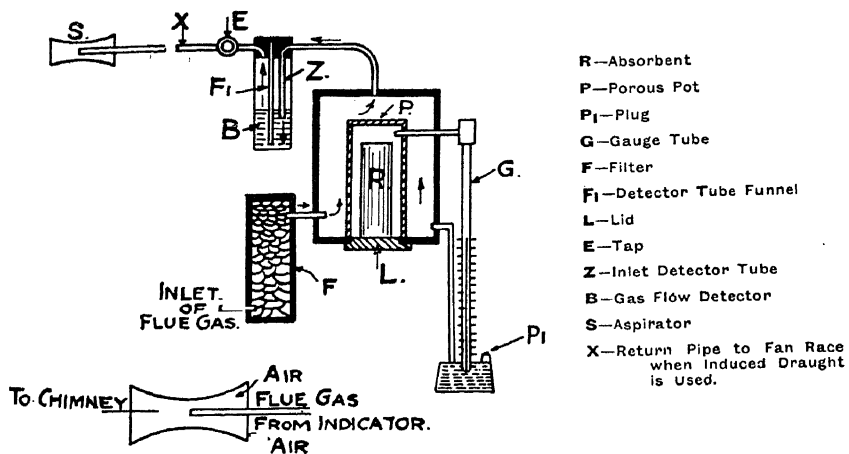


Fig. 92.—W.R. Carbon Dioxide Indicator.

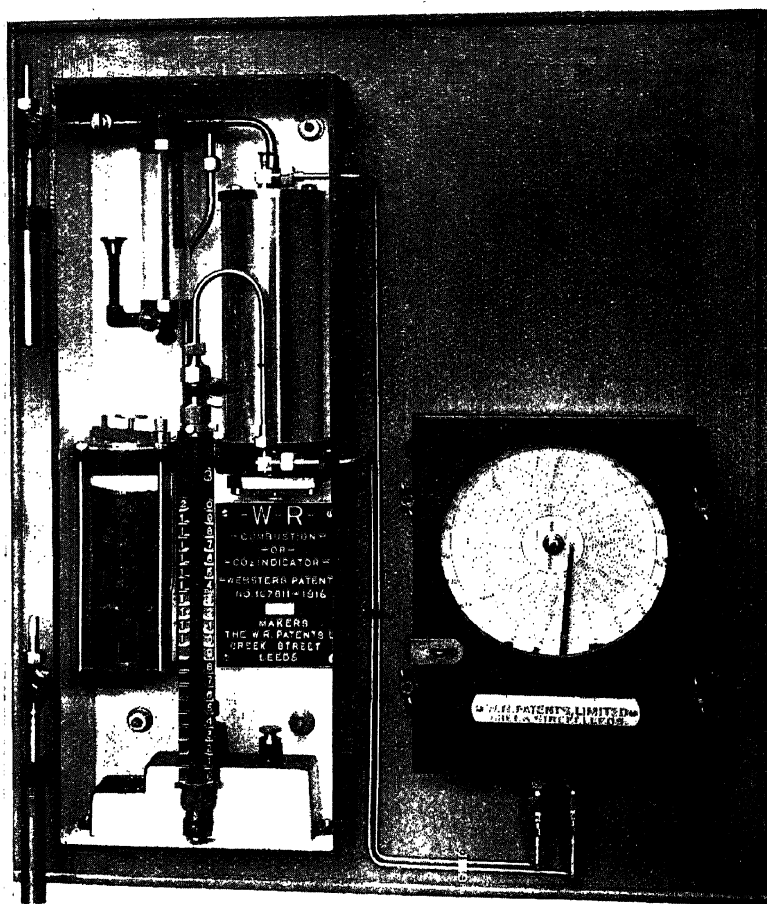


Fig. 93.—W.R. Carbon Dioxide Indicator and Recorder.

reagent. This results in a reduction of the pressure of the gases in this vessel below that in the outer vessel, which reduction is shown by the water column gauge. The amount of movement of the water column will depend on the quantity of carbon dioxide present in the gases.

The Electroflo recorder is also used for carbon dioxide, and a departure has been made from the usually conceived ideas for constructing this type of instrument. All glass-ware and rubber tubing have been dispensed with, a motor-driven aspirator is employed, and the whole of the working parts are submerged in oil; water has been entirely eliminated. A large absorption vessel is incorporated which permits

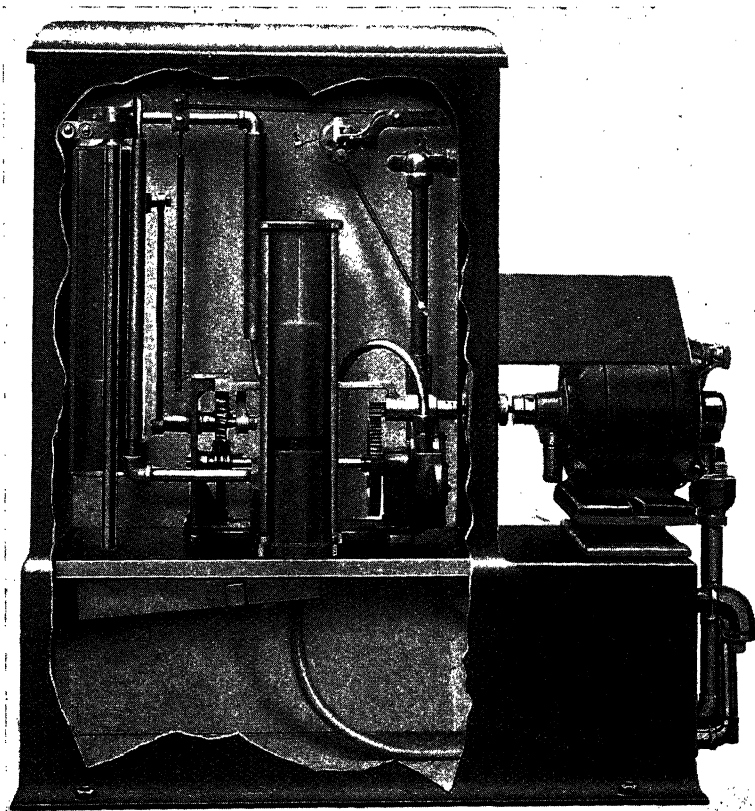


Fig. 94.—Electroflo Carbon Dioxide Recorder.

the instrument to be used for periods up to several months without attention. These special features are clearly shown in *Fig. 94*. Both indicator and recorder can be used, and in one type of recorder a strip chart is employed which may be obtained in a length to give several weeks' record. *Fig. 95* illustrates a combined indicator and recorder with circular chart.

The method of sampling is very important. Samples of the gases taken over a period of seconds and known as "snap" samples are of little value for showing the average conditions unless the conditions remain constant over long periods, and this is rarely the case in rotary kiln practice. It is therefore very desirable that the sampling should be extended over as long a period as possible. A sample taken

over a period of ten to twenty minutes' duration is satisfactory, but for some purposes it is better to take a sample over a much longer period, say twelve or twenty-four hours. With recording instruments the samples are generally obtained over a period of short duration, but as there are many such samples during a period of one hour a good average result is obtained.

When using the Orsat apparatus it is usual to collect the sample in a vessel and to take from it the 100 cc. required for analysis. Where no permanent arrangement exists for sampling it is possible to take a short-period sample quickly from two Winchester quart bottles, as shown in *Fig. 96*. The bottle in which it is desired to obtain the sample is completely filled with water, and by means of a syphon it can be made to empty itself into the other bottle, the rate of flow being under control.

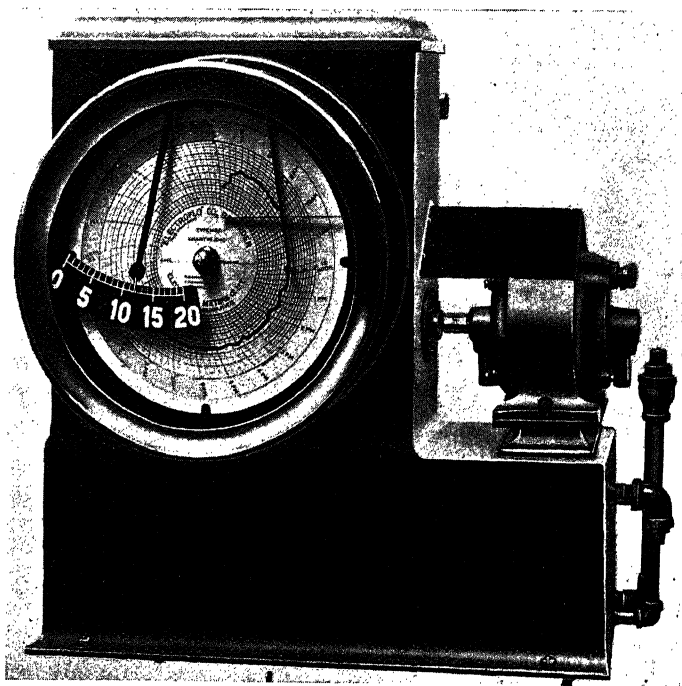


Fig. 95.—Electroflo Instrument with Indicator and Chart.

It is an easy matter to adjust the rate of sampling so that an average sample can be obtained over a period of twenty minutes. It is very essential that the water employed is free from any dissolved constituent which would absorb the carbon dioxide, and it is advisable to bubble the gas through the water for as long a period as possible before the sample is taken so that the water is saturated with carbon dioxide. Sometimes, to ensure that there is no absorption of the carbon dioxide by the water, a layer of paraffin is placed on top of the water.

There are several continuous samplers available, but in selecting an instrument it is desirable to see that proper provision is made for regulating the rate of aspiration. If the water is allowed to flow from a tap in the bottom of the sampling vessel the head of water will gradually decrease, with consequent decrease in the rate of sampling. In the best type of instrument a float chamber similar to that used in a

CONTROL OF ROTARY KILNS

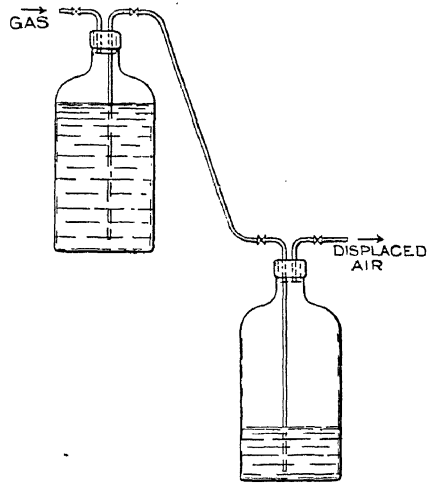


Fig. 96.—Temporary Gas Sampling Apparatus.

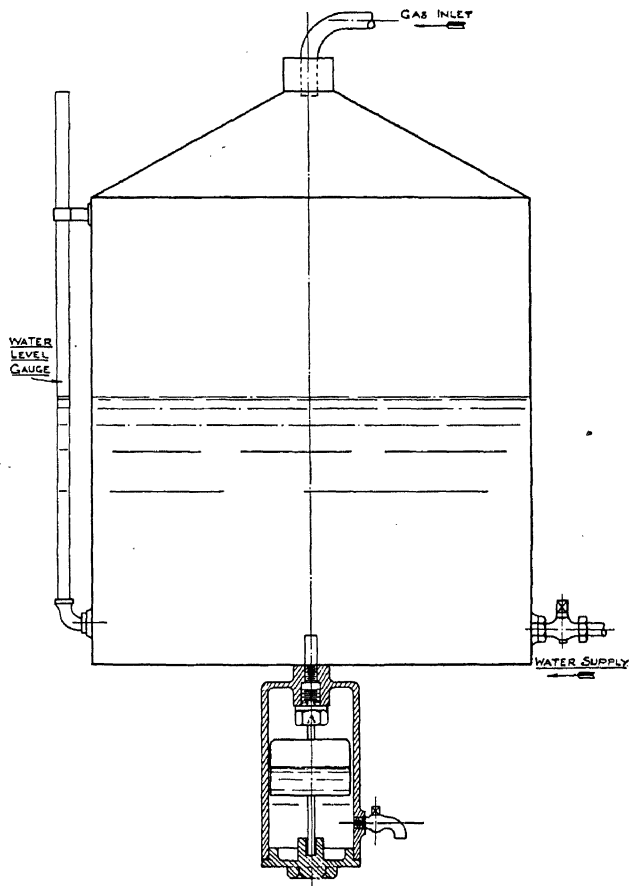


Fig. 97.—Sampler controlled by Float Chamber.

carburetter is used (*Fig. 97*). The water is drawn off from the float chamber and the rate is therefore constant over the whole range.

Measurement of Slurry Feed

In the wet process the slurry is usually fed into the back end of the kiln either by means of a spoon-feed gear or by bucket elevator. The spoon-feed gear (*Fig. 98*)

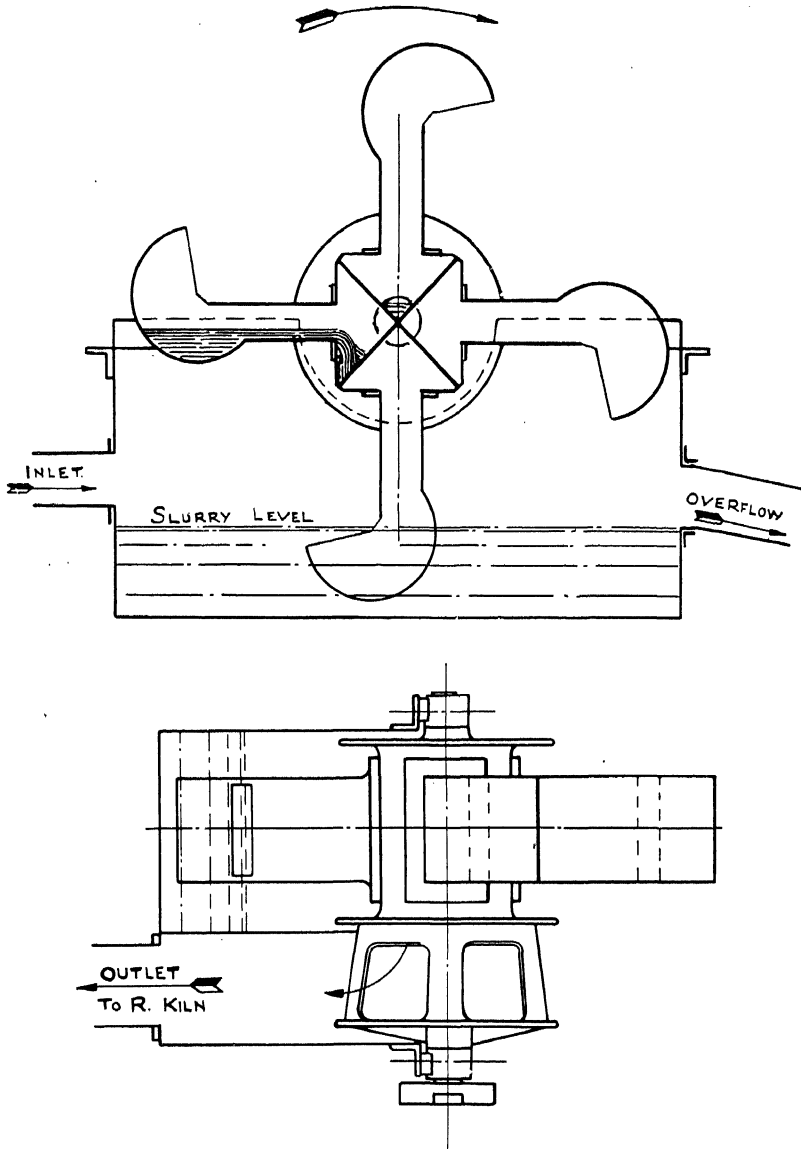


Fig. 98.—Slurry Spoon-feed Gear.

consists of a wheel having four or more hollow arms on the extremities of which are fixed buckets. As each arm revolves to the top centre the slurry in the bucket flows down the hollow arm into the hollow trunnion which is connected to the pipe

for feeding the kiln. This apparatus is driven by a variable-speed motor so that the rate of feed can be controlled. Provided the level of the slurry in the base of the apparatus is kept constant, it is an easy matter to determine the weight of material

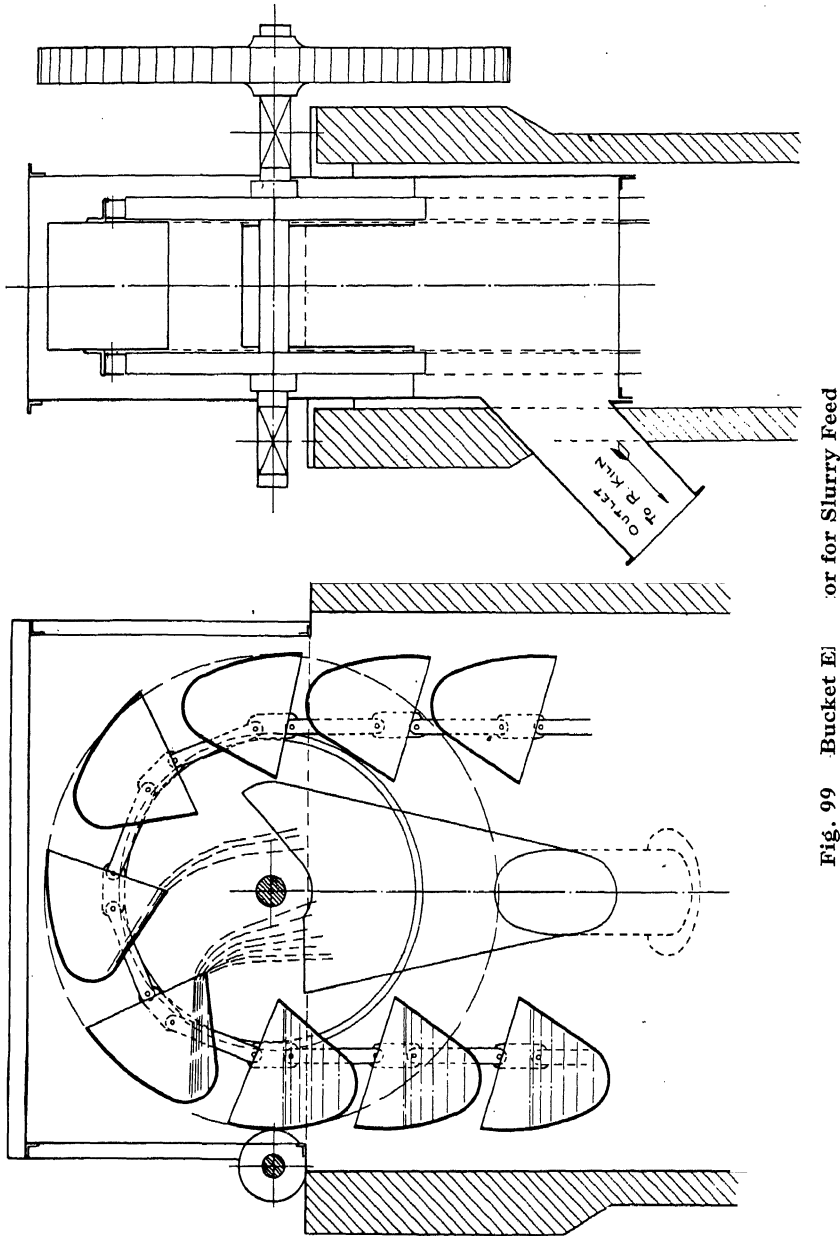


Fig. 99 Bucket Elevator for Slurry Feed

fed into the kiln over a period by counting the number of buckets-full which are tipped in. This is readily done by means of a counter. With the bucket-elevator type of slurry-feeder (*Fig. 99*) the quantity of material may be determined by the same means as is adopted for the spoon-feed gear. The bucket-elevator should also be

driven by a variable speed motor so that the operator may have exact control of the rate of feed to the kiln.

Other forms of apparatus could be used for measuring the rate of feed, such as the Venturi meter placed in the pipe-line, or one of the many types of measuring apparatus employing a weir. None of these latter methods has been extensively used in this country owing to the colloidal nature of the slurry, which results in the building up of the material in various parts of the apparatus.

Moisture in Raw Materials

The moisture in the prepared raw materials fed into the kiln can be determined either by a snap sample or from a sample obtained continuously. Continuous sampling is not easy owing to the colloidal nature of many of the materials used, but where the slurry is passing along an open trough a simple sampler can be made by mounting a flat-rimmed wheel in the centre of the trough and at such a height that the slurry in passing under it causes the wheel to rotate; while rotating the rim of the wheel picks up a small quantity of the slurry, which can be scraped off into a sampling container.

Air and Gas Pressures

It is essential that the pressure of the gases in the kiln and of the air in the firing pipe be known. The following are the usual points where readings are determined: (1) draught in back end of the kiln, (2) pressure in firing hood, (3) static pressure of the air in the coal-firing pipe. Air or gas pressures, whether positive or negative, are usually measured in inches of water column, generally referred to as "inches water gauge," although sometimes it is preferred to measure the column in millimetres of mercury.

The simplest form of gauge is the U gauge, which can readily be made from a piece of glass tubing bent to the shape which gives it its name. This type of gauge is satisfactory for measuring differences in pressure of $\frac{1}{2}$ in. or more, but smaller differences are very difficult to read satisfactorily. It is very sensitive to sudden changes in pressure, which cause the water column to oscillate. A small amount of evaporation of the water or condensation of vapour in the air or gas in the pipe connecting the instrument to the point of measurement would cause the zero to change. It is easy to read the wrong leg of the U and record a positive pressure as a negative pressure, and vice versa. A difference of pressure causes one leg of the U to rise above the other, but as the scale has reference to only one leg a difference of pressure of 1-in. water gauge corresponds to only half an inch on the scale; this makes the instrument very difficult to read where the difference in pressure is small. In spite of these disadvantages this type of gauge (*Fig. 100*) has been extensively used for many years.

Most of the difficulties associated with the U gauge have been eliminated in the Arkon full-scale gauge. In this instrument a single straight glass tube is connected at one end to a vessel having an area many times that of the bore of the glass tube. The other end of the tube is connected to the source of pressure difference. When the difference of pressure is applied to the open end of the tube the column of water will be raised or depressed depending upon whether the pressure is negative or positive, but the level in the vessel will for all practical purposes remain unchanged owing to its area being so much greater than that of the tube. The column of water

will therefore move up or down the scale by the full amount of the pressure difference, or, in other words, a pressure of 1-in. water gauge will correspond to 1-in. movement along the scale. The fact that the vessel is of large area means that the loss of some of the water, or the addition of water due to condensation, will not appreciably affect the zero.

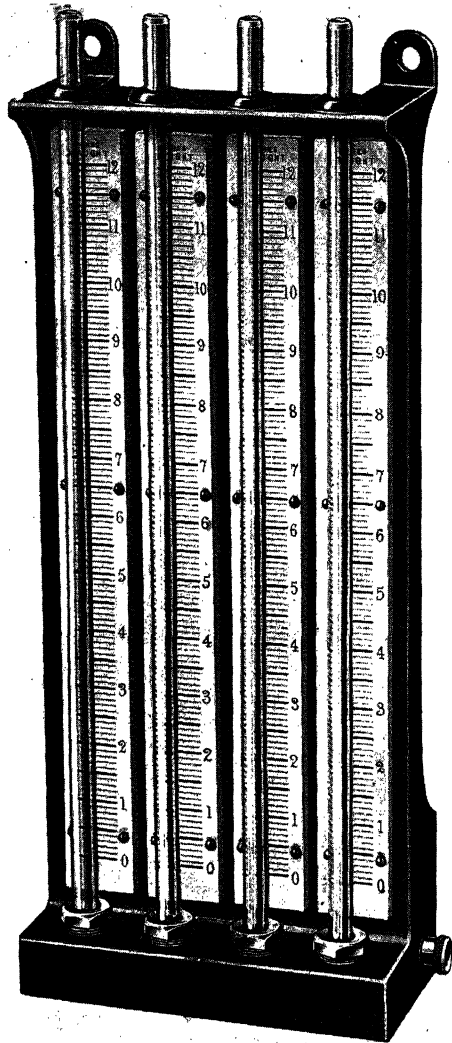
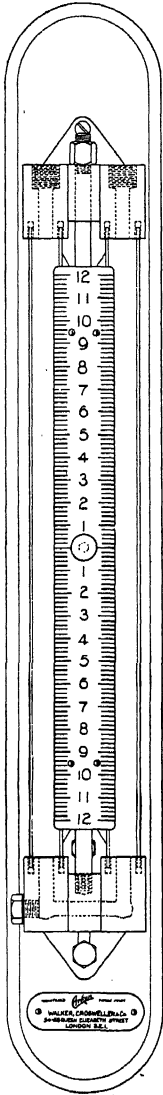


Fig. 100.—"U" Pressure Gauge. [Fig. 101.—Multi-point Arkon Pressure Gauge.

A number of gauge glasses can be connected to a common vessel. This ensures that the readings of the gauges are comparative, which is rarely the case with a number of U gauges unless the zeros are constantly checked. A multi-point full-scale Arkon gauge suitable for measuring negative pressures is shown in Fig. 101, and in Fig. 102 is shown a single-point gauge for measuring both positive and negative pressures.

Various methods have been adopted to increase the length of scale of water-column gauges. In some cases this has been done by mechanical means or by the use of two fluids of different specific gravities. Another satisfactory arrangement is to place the glass tube at an angle (*Figs. 103 and 104*). By this means it is possible to multiply the scale reading many times, but if the slope of the tube is too gradual

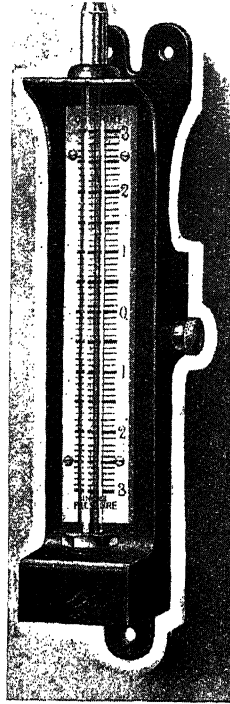


Fig. 102.—Arkon Single-point Pressure Gauge.

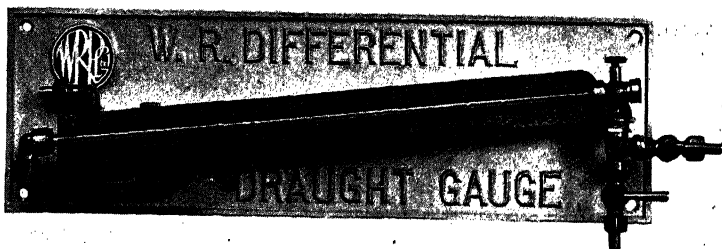


Fig. 103.—Draught Gauge with Sloping Scale.

the meniscus becomes very indefinite and difficult to read, while at the same time the gauge becomes very long. A modification of this form of gauge is one employing a curved tube which is rather flat at the beginning of the scale. This is done for the purpose of increasing the length of scale over the lower part of the working range of the gauge, or when used in conjunction with a flow meter it enables the scale to be equally divided. This instrument (*Fig. 105*) is known as a curved tube manometer.

Where considerable differences in pressure exist the Bourdon tube gauge may be employed, but this is not sufficiently sensitive for differences of pressure of 1-in. or 2-in. water gauge. There has therefore been developed a type of gauge employing a sensitive diaphragm which for a difference of 2-in. water gauge will exert an operating force of 1 lb. Although the diaphragm is of very thin metal it has been possible by specially shaping its corrugated surface to make it strong and yet retain its sensitiveness. *Fig. 106* shows the construction of the diaphragm, and *Fig. 107* the

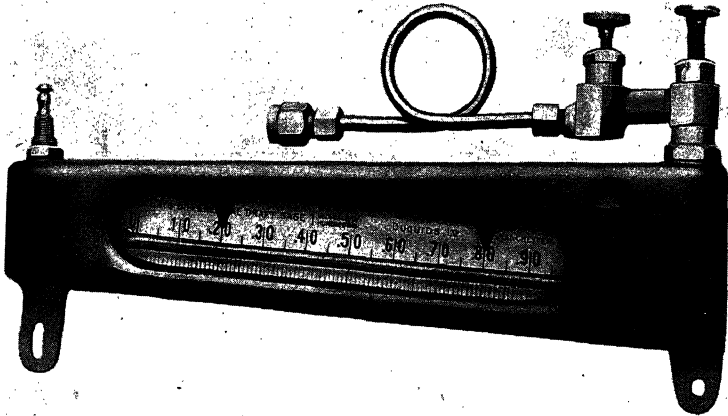


Fig. 104.—Draught Gauge with Sloping Scale.

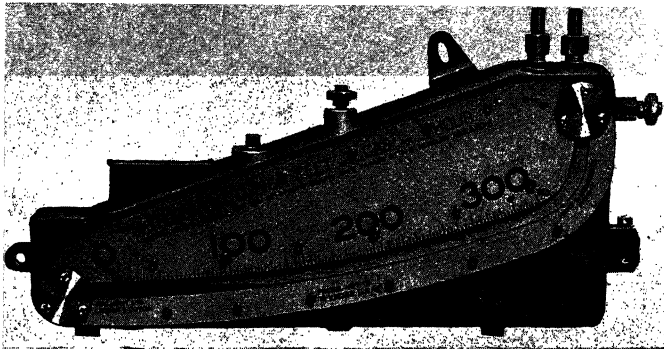


Fig. 105.—Curved Tube Manometer.

appearance of this form of gauge suitable for measuring pressure differences at three positions. With this instrument it is desirable to have some form of safety valve which may be a water seal, as it will not withstand pressures much in excess of the range of calibration. Where the pressure fluctuates violently it is necessary to introduce a damping device, which may take the form of a small capillary placed near the gauge at a convenient point in the pipeline.

One of the most difficult positions for a pressure gauge is, perhaps, the firing hood of a rotary kiln. The pressure difference at this point is small (about -0.3 in.

water gauge), but it may at times fluctuate violently due to the "puffing" action in the burning zone of the kiln, which is sometimes caused by insufficient draught. Under such conditions it is perhaps best to install a type of gauge which employs oil instead of water as the operating fluid. The oil has a damping effect, but where

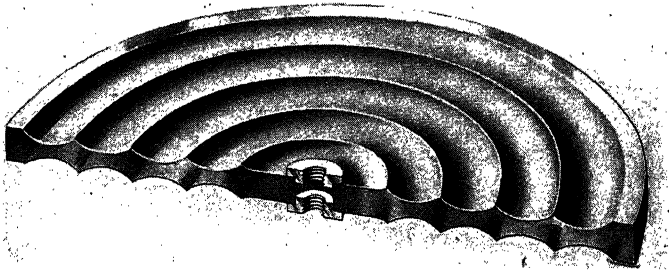


Fig. 106.—Pressure Diaphragm.

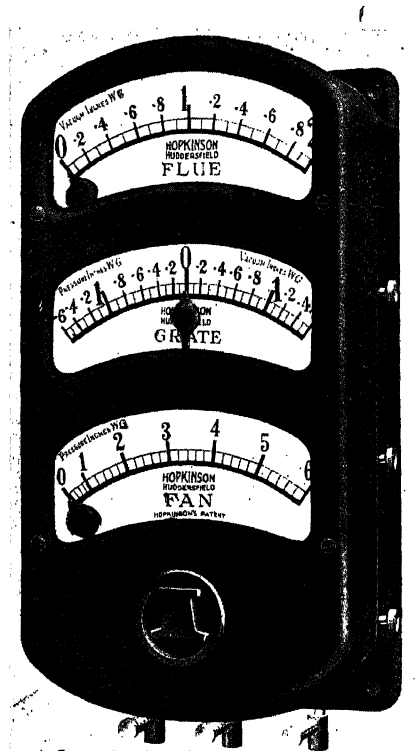


Fig. 107.—Gauges for Measuring Differences of Pressure.

the fluctuations in pressure are very violent a damping dash-pot either of the air or oil type may be introduced. With this type of gauge the scale is calibrated in inches water gauge, and a very open scale is obtained by a system of levers which multiplies the movement of the oil column. Fig. 108 shows a multi-point gauge with edgewise scales which employs oil as an operating medium and a system of

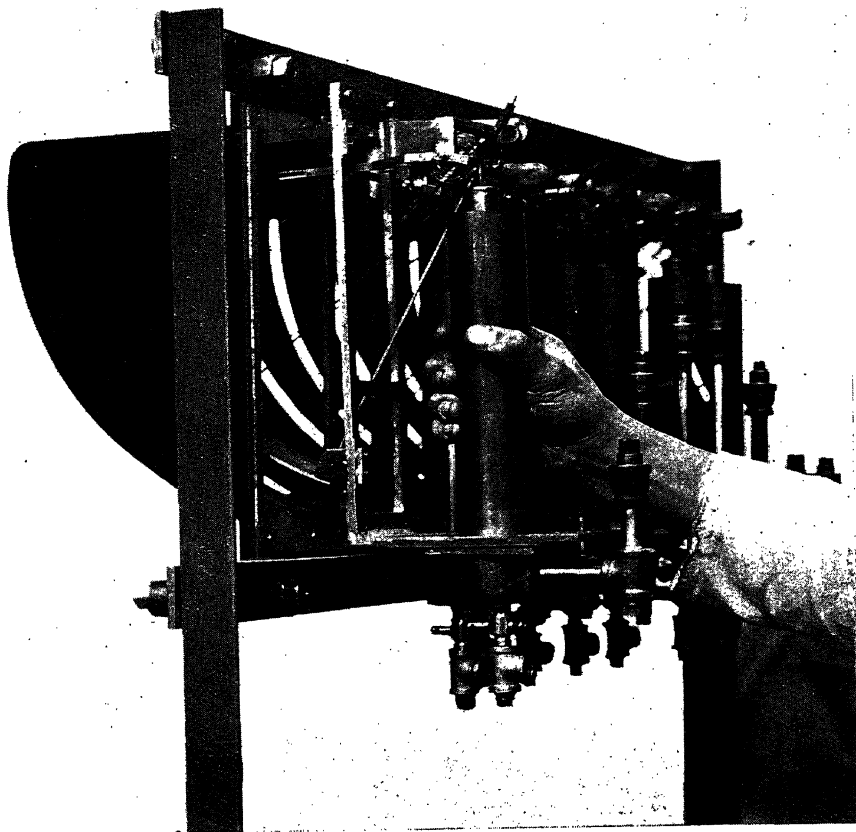


Fig. 108.—Multi-point Pressure Gauge with Edgewise Scales.

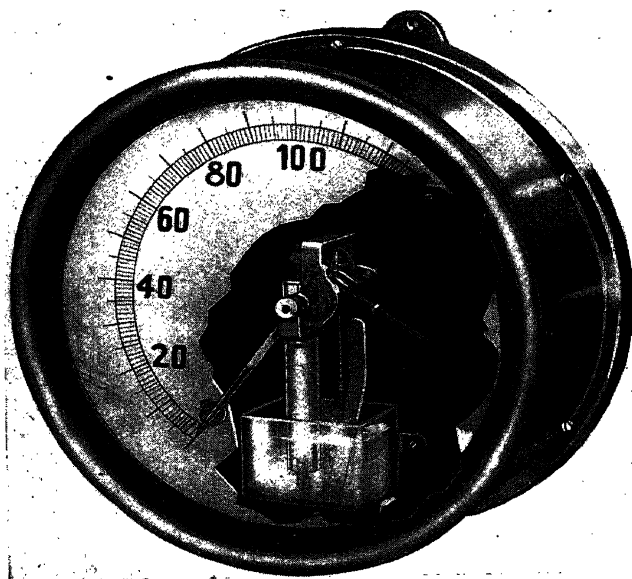


Fig. 109.—Pressure Gauge with Circular Scale.

levers for multiplying the column movements. *Fig. 109* illustrates a similar type of instrument but with circular scale.

Optical Pyrometers

The temperature of the material in the burning zone of a rotary kiln is about 1,500 deg. C., and that of the flame is even higher. It is therefore impossible to use instruments such as the pyrometer which necessitate contact with the material of which the temperature is to be measured. It is necessary to use an instrument which depends either on optical means or on the heat radiated from the material. When the temperature of a body is sufficiently high some of its energy is visible as light. Unfortunately the optical method of measurement cannot be relied on where accuracy is of importance, as the eyes of two observers are rarely affected to the same extent. The eye which measures the degree of brightness is affected by the mass and the length of time it is focused on a hot body. The comparative brightness of the surrounding space will also cause an apparent difference in the brightness

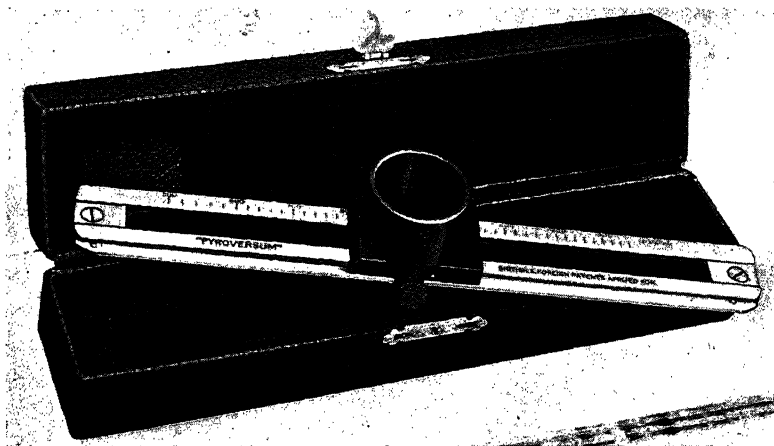


Fig. 110.—Optical Pyrometer.

intensity. For the same reasons optical pyrometers which employ an absorbing medium between the hot body and the eye cannot give consistent and accurate results except when the observer has had long experience.

A simple form of optical pyrometer which may be classed with the last-mentioned type has been developed (*Fig. 110*). It consists of a piece of glass about 6 in. in length, which is smoked in increasing intensity from one side to the other and mounted in a frame along which an eye-piece can be moved. The pyrometer is calibrated against a standard candle by moving the eye-piece along the scale until a point is found where the image of the candle disappears entirely. This point corresponds to a definite and known temperature, and is marked for future reference. Before an observer can use the instrument he must compare his vision with that of the person who calibrated the pyrometer by observing the number of degrees the eye-piece has to be moved above or below the standard position to obtain complete elimination of the image of the candle. The observer may then direct the eye-piece towards the hot body, and by moving the eye-piece across the smoked glass a point can be found where the hot body can no longer be seen. The apparent temperature is then

read from the scale, and to this must be added or subtracted the difference between the standard calibration and the calibration of the actual observer.

Another form of optical pyrometer which gives reliable results employs a wire filament heated by an electric current (*Fig. 111*). The filament, which is specially "aged" so as to prevent its displaying, after prolonged use, fluctuations in brightness when a definite current is passing, is mounted in a tube fitted with an optical system whereby the hot body can be focused at a point in the tube adjacent to the filament. The filament is in series with an ammeter and variable resistance. By varying the latter the temperature of the filament can be made to correspond with the focused hot body until there is no difference in the brightness. The change of resistance

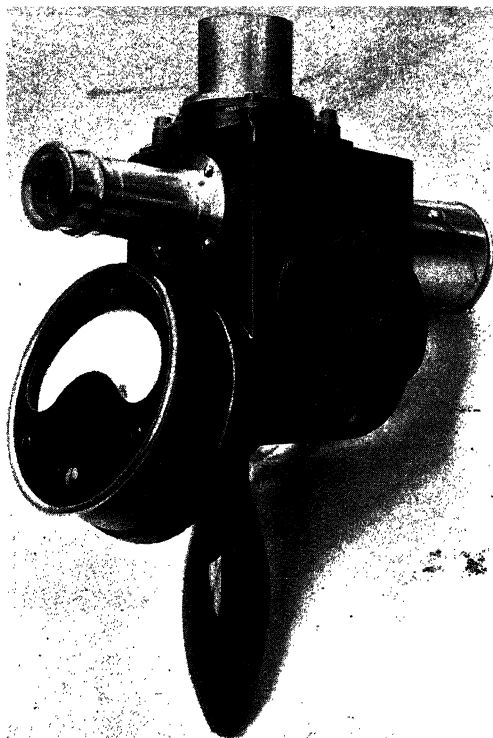


Fig. 111.—Hot-Wire Optical Pyrometer.

produces a change of current which is shown in degrees of temperature by the ammeter, which has been previously calibrated. The eye is able to detect a very small difference in the brightness of the filament and hot body, and there is no difficulty in reading as small a difference as 5 deg. F. at 1,000 deg. F.

Several types of pyrometers depend for their operation on the heat radiated from a black body, but all these have an optical system which causes the radiated heat waves to be focused at a point so as to act on a thermo-couple or other means of temperature measurement. This principle is employed in the Féry pyrometer, of which there are several forms. The earlier type of instrument is heavy and cumbersome, the optical system requiring the use of a tripod as it was necessary to focus the object. Improvements in construction have, however, been effected and

it is now possible to obtain an instrument (*Fig. 112*) which is portable, can be supported by one hand, and does not require focusing provided certain simple instructions are carried out. Accurate results are possible with this type of pyrometer provided the surface of the black body with which it is used completely fills the object glass of the optical system.

There is often considerable confusion as to what is termed a black body. A true black body will not reflect any light from surrounding sources, but will absorb

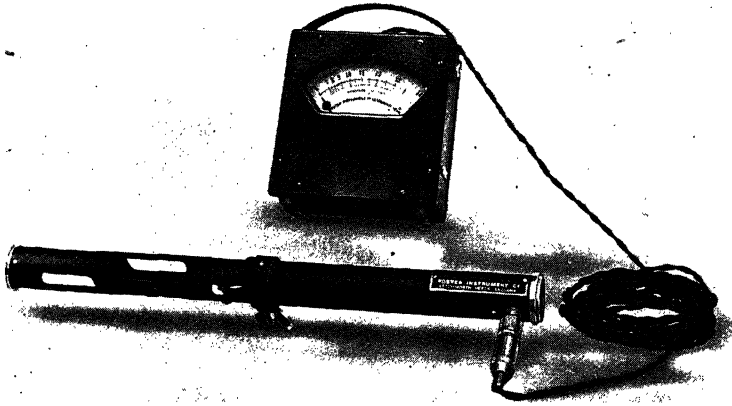


Fig. 112.—Portable Fery Pyrometer.

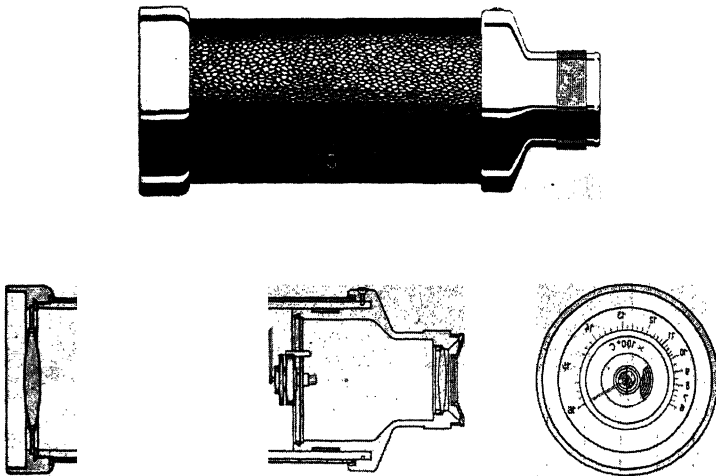


Fig. 113.—Radiation Pyrometer.

all the rays falling upon it. The inside of a furnace may be regarded as a black body provided the aperture through which observation is made is small, as all the radiated light must come from within the furnace. Where, however, an object can receive light from an external source, or it is not a true black body, radiant energy will be absorbed or reflected from its surface and the reading of the pyrometer will be incorrect. An object which under certain conditions may be a true black body may be changed by the formation of a film of oxide when exposed to the atmosphere. It will thus be seen that under certain conditions great care is necessary in using this

type of instrument. The burning zone of a rotary kiln may be taken as a true black body.

Another form of radiation pyrometer (*Fig. 113*) employs, instead of the thermocouple, a bi-metal strip which is formed into a coil. By an optical system the radiant heat is focused on to the bi-metal coil and, due to the difference in expansion of the two metals from which it is made, the coil tends to increase or decrease in diameter depending on the temperature of the object being measured. The movements of the coil are transmitted to a needle which moves over a scale. This instrument is fully compensated for changes in air temperature and for heat which may be radiated on to it. Its dimensions are about 8 in. long by $2\frac{1}{2}$ in. diameter; it is therefore very convenient for carrying and, as no focusing or other adjustment is required, readings may be quickly obtained.

Weight of Fuel

With some exceptions coal in pulverised form is used for producing the high temperature necessary for bringing about the chemical changes which take place

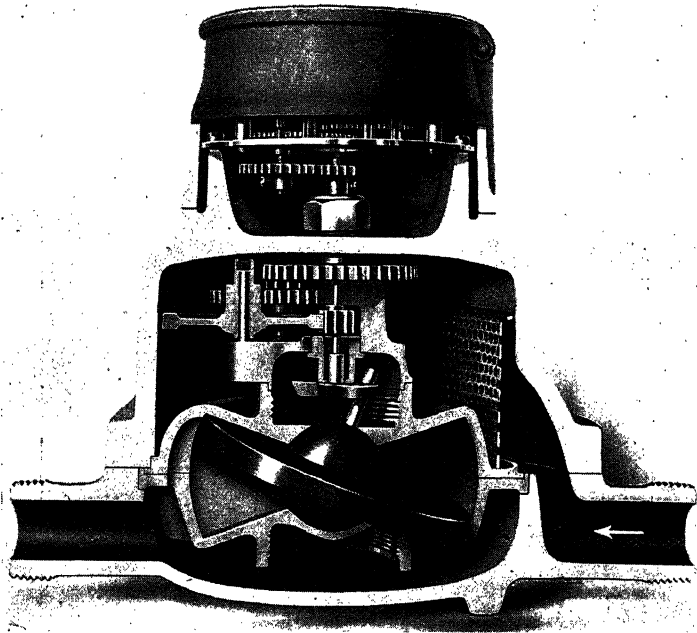


Fig. 114.—Oil Meter.

in a rotary kiln. The exceptions are generally plants situated near to a cheap source of oil fuel. When oil fuel is used it is easy to measure the quantity consumed, as there are many forms of meters available, such as the rotary or displacement type (*Fig. 114*). It is not proposed to deal with these in detail, as the application of oil fuel is limited.

Where coal is used it is generally weighed or measured before it is converted to powdered fuel. With the introduction of unit pulverisers it has become a relatively simple matter to determine the rate of feed by introducing a weigher or measurer between the coal hopper and the grinding unit. The coal is generally weighed by

a batch weigher, but in many cases it is simpler to use a meter which measures volume, the volume being subsequently converted into weight. The latter form of meter is known as the Cubimeter (*Fig. 115*), and consists of a short length of belt conveyor between two vertical plates placed on each side of it and a floating gate which measures the height of fuel. By suitable integrating means the cubical measurement of the coal can be determined over a period of time, and is shown on the indicator or recorder as the rate of feed in lb. or tons per hour. This form of measurement has the advantage that, in addition to the record of the quantity used in any period, it is possible to ascertain the rate of feed at any instant. The conversion from cubical measurement

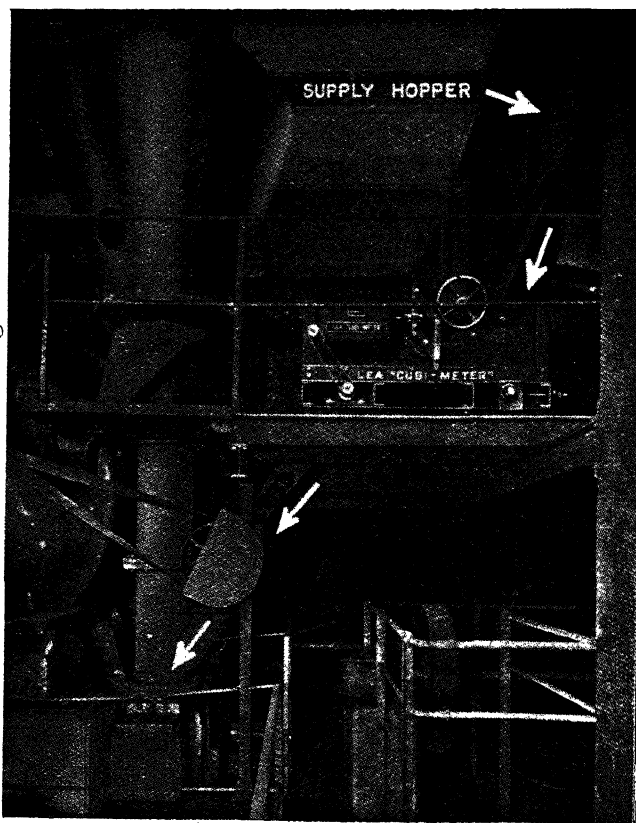


Fig. 115.—Cubimeter for Measuring Coal.

to weight involves the use of a constant which varies with different classes of coal and the moisture content. It is therefore necessary regularly to check the weight of a cubic foot of the coal used.

When it is desired to measure the coal delivered to the kiln in pulverised form in a system employing a storage bin for the ground coal it is usual to rely on recording the number of revolutions of a screw which propels the pulverised fuel through a pipe. This may at first appear to be a satisfactory method, but unfortunately coal does not flow regularly from the feed hopper to the screw, and consequently at times the screw may be partly or completely empty; further, the coal may tend to pack more tightly in the screw at one instant than at another.

Air Supply to Kiln

The air for combustion of the fuel in a kiln is introduced in two portions, known as the primary and secondary air supplies. The primary air is introduced with the fuel and may or may not be above atmospheric temperature; the secondary air supply, which is preheated, comes via the cooler where heat exchange takes place between the hot clinker and the incoming cool air. The secondary air enters the kiln through the hood around the burner pipe. It is almost impossible to get reliable measurements of the quantity of secondary air owing to the fact that not all of it passes up the cooler, there being considerable infiltration in the connections between the kiln and the cooler and the firing hood and the kiln. It is therefore necessary

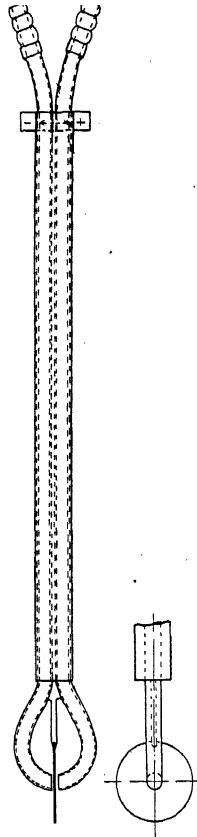


Fig. 116.—Pitot Tube for Dusty Positions.

to confine measurements to the primary air supply, and where this is thought desirable one of several means of measurement may be employed.

The commonest form of instrument is the Pitot tube (*Fig. 116*). This consists of two tubes of small bore arranged so as to have the end of one at right angles to the flow of air and the other facing the flow of air. These two tubes are placed in the position of average flow in the pipe, the other ends being connected to a differential gauge. When the pressure is positive, as on the discharge side of the fan, the tube at right angles to the flow will give the static pressure and the facing tube the sum of the static and velocity pressures, or total water gauge. If both the tubes are

connected to opposite sides of the same gauge the differential reading will give the velocity pressure. The conditions are somewhat different when the pressure is negative as on the suction side of the fan. The tube at right angles to the flow will then give the total suction and the facing tube the difference between the static and velocity pressures, when either is connected to one side of a U gauge.

It is possible to calculate from simple formulæ the volume passing through a duct in any unit of time when the velocity pressure, the cross-sectional area of the pipe, and the temperature of the air are known. The Pitot tube is satisfactory provided the air is measured before any pulverised coal is introduced into it. It is useless after the coal has been added, as the small tube quickly becomes blocked. Modifications of the simple Pitot tube have been made which it is claimed make it satisfactory for use in dusty positions, but it is far better to choose a position in the pipeline before the coal is added.

The Venturi meter (*Fig. 117*) may also be used for measuring the quantity of air. Its operation is dependent on the increase in velocity which is produced if the

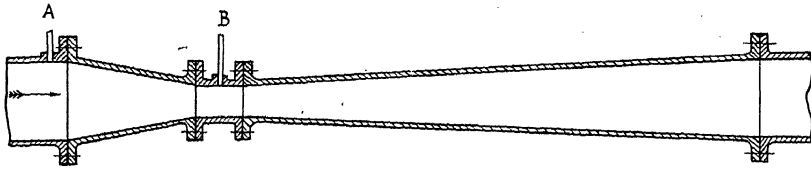


Fig. 117.—Venturi Air Meter.

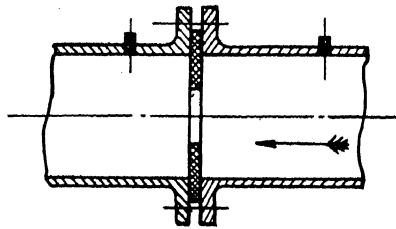


Fig. 118.—Orifice Type Air Meter.

cross-sectional area of a pipe is reduced and the resulting difference in pressure set up between two points in the pipe system a relatively short distance apart. An advantage of the Venturi meter is that the loss of pressure across the whole apparatus is very small, as with the correct proportioning of the up-stream and down-stream sides of the point of maximum restriction 85 per cent. of the head required for creating the velocity is recovered. As with the Pitot tube, a water column or other form of gauge is used for measuring the pressure difference, and this can be calibrated in terms of quantity.

Where it is not convenient to employ a Venturi meter, which generally occupies a considerable length of piping, an orifice type meter may be used. This consists (see *Fig. 118*) of a plate having at its centre a hole of smaller diameter than the pipe, which is introduced at right angles to the flow. This plate acts as a throttle and sets up a great difference in pressure between the up-stream and the down-stream sides; the difference is measured by a gauge either in terms of water gauge or directly in

terms of flow. The drop in pressure across the throttle is usually several inches water gauge, all of which is lost.

Clinker Temperatures

The temperature of the clinker on leaving the cooler should be as low as possible so as to ensure the maximum exchange of heat from the clinker to the secondary air supply, and to leave the clinker in a condition in which it can be satisfactorily handled by a belt conveyor or other means. Under proper operating conditions the temperature should be considerably under 200 deg. F. It is not possible to measure the temperature continuously, as it is below the limits of optical and radiation methods of measurement, and it would be very difficult to use a pyrometer owing to the fact that the cooler is rotating and the abrasive nature of the clinker would produce very rapid wear of anything in contact with it. The usual method is to take a sample from time to time and obtain its temperature with an ordinary thermometer.

Radiation and Convection Losses

It is frequently necessary to measure the shell temperature of a kiln or cooler, as with this information it is possible to calculate the loss due to radiation and convection. Various means are available for determining these temperatures, which vary from about 500 deg. F. downwards.

A special form of pyrometer which employs a strip-type thermo junction is particularly suitable for the purpose. The thermo strip, which is about $\frac{1}{2}$ in. wide and 8 in. long, is mounted in a light frame like a bow and stringer on the end of a long light handle. Contact between the centre of the thermo strip or stringer and the surface the temperature of which is to be measured is all that is necessary. The temperature is shown on an indicator of the usual type.

Another and direct method of measuring radiation and convection losses is by a surface-heat flow gauge. This apparatus is relatively simple, and, although the results may not be so accurate as other more laborious methods, it has the advantage of being comparatively rapid in use and is capable of giving results without troublesome calculations. An instrument suitable for use on a flat surface is shown in *Fig. 119* and back and front views are shown in *Fig. 120*. The essential parts of the instrument consist of an air chamber connected to a sensitive manometer and a restricted orifice which takes the form of a capillary tube connected to the chamber. When the exposed surface of the chamber is placed so that it receives a flow of heat, a rise of pressure of the air inside the chamber will take place and this will be proportional to the rate of heat flow into the chamber. When the pressure rises some of the air will escape through the capillary tube, but a condition will eventually be reached when the rate of loss of air due to expansion will exactly compensate the rate of rise of pressure due to the flow of heat into the chamber. It is the measurement of the steady pressure which is taken as the measure of the flow of heat. The face of the chamber which receives the heat is matt black on both surfaces, while the rest of it is polished. The chamber is mounted inside a recessed water jacket with polished walls. It is necessary to calibrate the instrument by direct experiment; the method used is to compare the reading of the apparatus with the known heat losses from a copper plate which is electrically heated. By varying these known losses a calibration graph showing the relation between the manometer readings and the radiation and convection losses in B.T.U.'s per square foot per hour can be obtained.

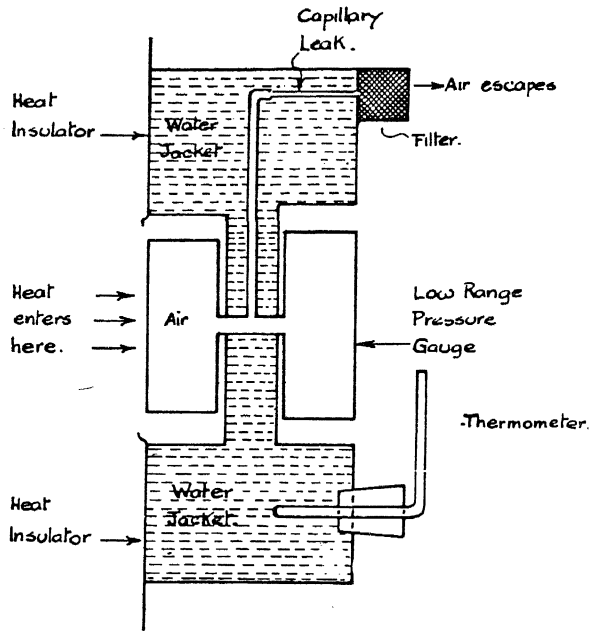


Fig. 119.—Surface Heat Gauge.

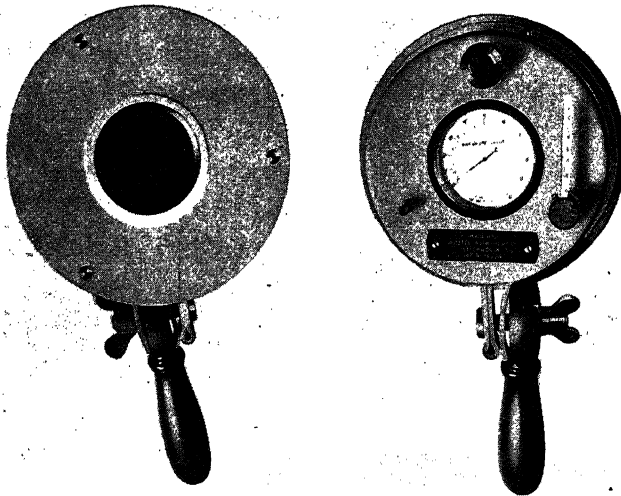


Fig. 120.—Surface Heat Gauge.

Clinker Weighing

The weighing of clinker is a more difficult problem than the weighing of other materials, as owing to its abrasive nature working parts such as knife edges are subject to very excessive wear which quickly upsets the accuracy of the weigher. For the same reason meters which depend on cubical measurement have not so far proved successful. When the weight is determined it is usual to use a batch weigher. One



Fig. 121.—Kiln Gas Analysis.

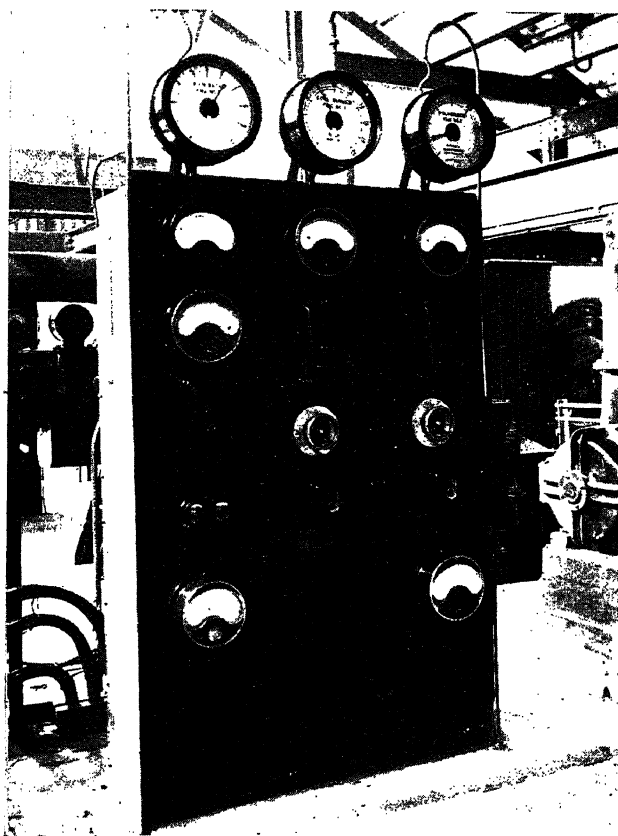


Fig. 122.—Kiln Control Panel.

type consists of a circular drum divided into four compartments, constructed in such a way that when a certain weight of clinker has passed into the uppermost compartment the centre of gravity is so altered that the drum is made to rotate; the full compartment then empties itself and the one next to it takes up the position formerly occupied by the one which has just emptied. The number of times the machine tips is recorded by a counter, but the total weight during any period has to be calculated; this involves the use of a constant previously determined.

Typical works installations of some of the recording apparatus described in this chapter are illustrated in *Figs. 121, 122, and 123*. *Fig. 121* shows combined

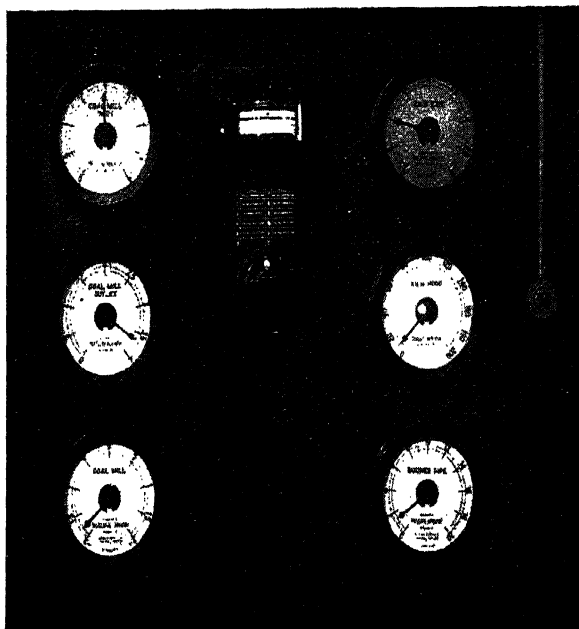


Fig. 123.—Kiln-Control Panel with Twelve-point Pyrometer Indicator.

CO₂ and oxygen recorder, katharometer for electrical CO₂ recorder, long period gas samplers, and Orsat apparatus. *Fig. 122* is a view of a kiln-control panel fitted with draught and pressure indicators, kiln-speed, coal-feed, and slurry-feed control panels. *Fig. 123* illustrates a kiln-control panel fitted with pyrometer indicator with twelve-point switching arrangement, draught and pressure indicators.

The foregoing does not presume to have covered all the means available for determining the many factors which enter into the control of the operations involved in a rotary kiln, but an endeavour has been made to show the principles involved and the manner in which many types of instruments are being usefully applied to a manufacturing process which still requires the skill and judgment of the human being.

CHAPTER XI

THE REACTIONS IN BURNING CEMENT

As has been described earlier, the drying and burning of slurry take place in one operation in the rotary kiln. The main processes in this operation are (1) drying the slurry, (2) dehydrating the clay and decarbonating the chalk or limestone, and (3) sintering or clinkering the material.

Drying the slurry consists in raising its temperature to 212 deg. F., converting the water into steam (which is costly in heat, as the latent heat is 967 B.Th.U. per lb. of water), and raising the steam so formed to the exit-gas temperature. The specific heat of steam is high (about 0.46). This drying of the slurry requires about 10 per cent. of the standard coal* to clinker, or about 40 per cent. of the total fuel consumption.

The dehydration of the clay in the slurry occurs at 842 deg. F., and requires a very small amount of heat, usually rather less than $\frac{1}{3}$ per cent. of standard coal to clinker, or less than 2 per cent. of the total fuel consumption.

Decarbonation consists in driving off carbon dioxide from calcium and magnesium carbonates. The dissociation constants for CaCO_3 and MgCO_3 are 711 and 387 B.Th.U. per lb., and the heat required for a normal slurry is about $6\frac{3}{4}$ per cent. of coal to clinker, or about 27 per cent. of the total fuel consumption.

During sintering or clinkering, part of the material melts and part remains solid. The heat of formation of the flux takes a very small amount of heat, amounting to about $\frac{1}{3}$ per cent. of standard coal to clinker, or about $1-1\frac{1}{4}$ per cent. of the total fuel consumption (flux taken as 24 per cent. of the clinker).

During the formation of the calcium silicates, aluminates, and ferro-aluminate, an exothermic reaction occurs, that is during their formation heat is given out, so that, instead of requiring heat for the reactions, heat is liberated and helps on the reactions. In the early days this was considered to be a large quantity, and some investigators thought that all that was required was to raise the temperature of the material to a little over 1,000 deg. C. and the temperature would then rise to a clinkering temperature of, say, 1,400 deg. C. without the assistance of external heat.

In 1904 Richards stated that this exothermic reaction liberated 750 B.Th.U. per lb. of clinker. Le Chatelier at that time made this figure 330 B.Th.U. per lb. Later Soper, Tschernobaeff, Dormann, Coghlan, and Nacken found values of from 180 to 280 B.Th.U. per lb. The most recent value found by Schwiete and Elsner von Gronow is 214 B.Th.U. per lb., and this is accepted as accurate nowadays. It is not a large amount, and is equivalent to an addition of $1\frac{3}{4}$ per cent. of standard coal to clinker.

It is unlikely that this additional evolution of heat takes place by itself. Two other reactions which are endothermic take place at the same time, namely heat supplied for the formation of glass, which is stated to be equivalent to $\frac{1}{3}$ per cent. standard coal to clinker, and also the latent heat of fusion of the glass, which may amount to the equivalent of $\frac{1}{3}$ per cent. of standard coal to clinker. It is therefore thought that the balance of the exothermic reactions left after these two deductions may amount to about 1 per cent. This exothermic reaction comes at a stage where the temperature of the clinker is at its maximum, which is not easy to reach and

* See footnote on p. 162.

maintain, and, while it must assist the process of clinker formation, it is not noticeable to the kiln operator.

As the clinker cools the molten glass solidifies as a glass or it may crystallise, or usually reach some intermediate stage where the product is partly solid glass and partly crystallised glass. During solidification the heat of fusion is recovered and goes towards preheating the air for combustion, but its value is very small.

The sensible heat in the clinker is largely recovered in the air for combustion which passes through the clinker cooler, the only loss being the heat in the clinker as it leaves the cooler, which usually amounts to only a fraction of 1 per cent. of standard coal to clinker.

Other heat losses are by radiation, convection, and conduction through the shells of the kiln and the cooler, which may be about 4 per cent. to 4.5 per cent. of standard coal to clinker, and loss of heat in the combustion gases which is proportional to the exit gas temperature ; this is, say, 4 per cent. to 5 per cent. of standard coal to clinker.

The foregoing is a brief summary of the reactions which take place in a rotary kiln, and the heat required to effect them.

CHAPTER XII

THE HEAT BALANCE IN ROTARY KILNS

THE problem of the efficient utilisation of heat when clinkering raw material in a rotary kiln is somewhat similar to that of the conversion of heat into steam in a boiler. Investigation into the amount of heat dissipated and wasted in cement kilns necessarily follows somewhat the procedure adopted in investigating the efficiency of steam boilers. The total heat given out by the coal used in making one ton of cement clinker is ascertained and compared with the heat which is theoretically necessary. In the compilation of balance sheets showing the heat distribution in rotary kilns, the earlier chapter on the reactions in burning cement will have made it clear that there is still some uncertainty regarding details of the burning operation, but this is not sufficient to detract seriously from the value of a close study of heat balances.

The principal operations in which heat is usefully expended, recovered, or wasted may be summarised as follows :

- (a) Heat is usefully *expended* in—
 - (1) Drying the raw materials.
 - (2) Decomposing the calcium carbonate.
 - (3) Heating the raw materials to clinkering temperature.
- (b) Heat is *recovered* from—
 - (4) The cooling of the hot clinker.
 - (5) The combination of lime and clay at the clinkering temperature.
- (c) Heat is *lost* in—
 - (6) Radiation from the kiln and cooler shells.
 - (7) The waste gases leaving the kiln.
 - (8) Imperfectly cooled clinker leaving the cooler.
 - (9) Heating air in excess of that needed for combustion.
 - (10) Imperfect combustion.

There is little difficulty in calculating the heat required to evaporate the moisture from the raw materials and to superheat the steam formed to the temperature of the exit gases.

It would be difficult to calculate directly the heat expended in raising the raw materials to clinkering temperature, as the specific heats of the raw materials when approaching the clinkering temperature are not definitely known, but this is not necessary. The heat expended in bringing the raw materials to clinkering point will be, under suitable conditions, largely recovered in the clinker cooler. The coal burned for the purpose of heating up the raw materials will only be that required to make good losses due to defective cooling, such as imperfectly cooled clinker, cooler radiation, etc.

The heat required to decompose the calcium carbonate and the heat evolved by the union of lime and clay at the clinkering temperature were explained at length in the previous chapter.

Accurate determination of the heat lost by radiation from kiln and cooler shells is difficult, owing to variation in the shell surface due to the presence of paint and rust. The temperature also varies considerably due to differences in the thick-

ness of the firebrick lining and the internal temperature. Heat is also lost from these parts by convection air currents. This is a very variable quantity, depending largely on whether the shell is protected from the wind and weather.

The total of these fuel losses is probably about 3 per cent. of clinker production, so that the variations indicated will not result in very wide error in making calculations.

The calculation of the heat lost in the waste gases presents little difficulty, provided the position chosen for the pyrometer is such that it gives the correct average temperature of the gases. A doubtful point is the specific heat of the gases at the higher temperatures, such as 900 deg. F., which are sometimes reached. Many valuable experiments on specific heats of gases have, however, been conducted, and the point becomes of less importance as modern methods of kiln operation and heat utilisation reduce the temperature of the waste gases.

It will be seen, therefore, that the total heat or quantity of coal required to produce one ton of clinker is capable of calculation, and very close agreement can be obtained in this matter with the coal consumption observed in actual practice extending over a long period.

For the purpose of preparing a rotary kiln heat balance, the following data are required :

Analysis of the coal used.

Percentage of CaCO_3 in dry raw material.

Percentage of moisture in raw material.

Percentage of moisture in coal.

*Standard coal to clinker, per cent.

*Standard coal factor $\frac{\text{calories as received}}{7,000}$

Exit-gas temperature.

Clinker temperature ex cooler.

Exit gas analysis CO_2 , per cent.

CO , per cent.

O_2 , per cent.

Organic matter in dry raw material, per cent.

The method of calculating the amount of heat passing in and from various directions and sources is best explained by taking a typical case and working it out in detail. For convenience the data used in the example which follows are set out below.

DATA REQUIRED.	HEAT BALANCE.
CaCO_3 in raw material	76.5 per cent.
Moisture in raw material	40.0 "
Moisture in coal	10.0 "
Standard coal to clinker	27.0 "
Standard coal factor = $\frac{\text{calories as received}}{7,000}$	0.85 "
Exit-gas temperature	700 deg. F.
Clinker temperature ex cooler . .	300 "
Preheated air temperature . . .	600 "
Exit-gas analysis CO_2	25.7 per cent.
CO	0.2 "
O_2	1.5 "
Organic matter in dry raw material .	1.0 "

* Standard coal is assumed to be a dry coal having a calorific value of 7,000 calories per gramme (12,600 B.T.U.'s per lb.).

In practice it is convenient to prepare tables for readily making the calculations. Useful tables are as follows :

- (1) CO_2 in exit gases per 100 lb. of clinker for varying percentages of CaCO_3 .
- (2) B.T.U. per lb. of CO_2 at different exit-gas temperatures.
- (3) B.T.U. per lb. of water at different exit-gas temperatures.
- (4) B.T.U. per lb. of air at varying exit temperatures.
- (5) Weight of water per 100 lb. clinker for varying slurry moistures.
- (6) B.T.U. required for dissociation of carbonates per 100 lb. of clinker.
- (7) B.T.U. of gases from combustion of 1 lb. of coal at different exit-gas temperatures.
- (8) Weight of excess air per 100 lb. of clinker for varying standard coal consumptions and $\text{CO}_2 + \text{CO}$ in exit gases.
- (9) B.T.U. in clinker leaving cooler at varying temperatures.

Debit Items

(1) HEAT CONTAINED IN CO_2 FROM RAW MATERIALS AT EXIT TEMPERATURES.—The weight (lb.) of CO_2 per 100 lb. of clinker will vary with the carbonate content of the slurry, and the heat (B.T.U.) in each pound of this gas varies with the back-end temperature.

Example.—

CO_2 at kiln exit temperature of 700 deg. F. = 145 B.T.U.'s per lb.

Weight when slurry carbonate is 76.5 per cent. = 57.7 lb.

Therefore $57.7 \times 145 = 8,366$ B.T.U.'s in CO_2 from slurry carbonate.

(2) HEAT CARRIED AWAY BY SLURRY WATER.—The weight of water from the slurry, including that from 1 per cent. of organic matter for each 100 lb. of clinker, is determined, allowing for variations in both slurry moisture and CaCO_3 . The heat units per pound of water will vary with the temperature of the exit gases.

Example.—

Slurry moisture 40 per cent. Carbonate 76.5 per cent. = 107.1 lb. water.

Exit temperature 700 deg. F. = 1,351 heat units per lb. of water.

$107.1 \times 1,351 = 144,692$ B.T.U.'s per 100 lb. of clinker.

(3) HEAT REQUIRED FOR DISSOCIATION OF CARBONATES.—A table can be prepared to give this figure as a direct reading according to the percentage of CaCO_3 .

Example.—

Carbonate in slurry 76.5 per cent. = 91,120 B.T.U.'s per 100 lb. clinker.

(4) HEAT IN COMBUSTION GASES AT EXIT TEMPERATURE.—The average B.T.U. in gases at the exit temperature from the combustion of one pound of coal, when multiplied by the percentage of standard coal burned, will give the heat loss from this source.

Example.—

Exit temperature 700 deg. F., standard coal used 27 per cent.

B.T.U. in gases per lb. of coal at 700 deg. F. = 2,143.

$2,143 \times 27 = 57,861$ B.T.U.'s per 100 lb. clinker.

(5) HEAT IN EXCESS AIR AT EXIT TEMPERATURE.—Determine the weight of excess air according to the known standard coal consumption and the known $\text{CO}_2 + \text{CO}$ in exit gas. Multiply this by the percentage of oxygen in exit gas. Having found the weight of excess air per 100 lb. of clinker from the table, find the B.T.U. per lb. at exit-gas temperature and multiply by the weight (lb.) of excess air per 100 lb. of clinker.

Example.—

$\text{CO}_2 = 25.7$ per cent. $\text{CO} = 0.2$ per cent. $\text{CO} + \text{CO}_2 = 25.9$ per cent.
 Standard coal 27 per cent.
 Weight of excess air $= 15.9$ lb. Oxygen $= 1.5$ per cent.
 $\therefore 15.9 \times 1.5 \text{ O}_2 = 23.85$ lb. excess air per 100 lb. clinker.
 Exit-gas temperature 700 deg. F.
 B.T.U. per lb. of air at 700 deg. F. $= 150 \times 23.85$ lb.
 $= 3,580$ B.T.U.'s per 100 lb. clinker.

(6) HEAT IN WATER IN COAL MOISTURE.—Weight of water per 100 lb. of clinker
 $=$ moisture in coal as received divided by the standard coal factor $\frac{\text{calories as received}}{7,000}$
 and multiplied by the standard coal consumption. Multiply this by the B.T.U.'s
 per lb. of water from the known exit-gas temperature.

Example.—

Moisture in coal, as received $= 10$ per cent.
 Standard coal factor $= 0.85$ „
 Standard coal consumption $= 27.00$ „
 Water per 100 lb. clinker $= \frac{10 \text{ per cent.} \times 27}{0.85} = 3.18$ lb.
 Exit-gas temperature $= 700$ deg. F.
 Heat in water in coal moisture $= 1,351$ B.T.U.'s $\times 3.18$ lb.
 $= 4,296$ B.T.U.'s per 100 lb. clinker.

(7) HEAT IN CO IN EXIT GASES.—Determine the B.T.U. per lb. of clinker from
 the known percentage of standard coal and the known $\text{CO}_2 + \text{CO}$ by gas analysis
 from the table. Multiply by the percentage of CO from gas analysis and by 100 for
 B.T.U. per 100 lb. of clinker.

Example.—

$\text{CO}_2 = 25.7$ per cent. $\text{CO} = 0.2$ per cent. $\text{CO} + \text{CO}_2 = 25.9$.
 Standard coal $= 27$ per cent.
 B.T.U. per lb. of clinker per 1 per cent. of CO $= 145.36$.
 B.T.U. per lb. of clinker $= 145.36 \times 0.2 \text{ CO}$.
 $= 29.07$ B.T.U.'s.
 $= 2,907$ B.T.U.'s. per 100 lb. clinker.

(8) HEAT IN CLINKER LEAVING COOLER.—Determine B.T.U. per lb. of clinker
 at the known temperature of the clinker leaving the cooler and multiply by 100 for
 B.T.U. per 100 lb. of clinker.

Example.—

Temperature of clinker leaving cooler $= 300$ deg. F.
 B.T.U. per lb. of clinker $= 47$
 B.T.U. per 100 lb. clinker $= 4,700$.

(9) HEAT IN AIR MOISTURE AND DUST LOSSES.—An allowance should be made
 of 4 B.T.U.'s for every 1 deg. F. in the temperature of the gases above 60 deg. F.

Example.—

Exit-gas temperature $= 700$ deg. F. $- 60$ deg. F. $= 640$ deg. F.
 Heat in air moisture, dust losses, etc. $=$
 $640 \times 4 = 2,560$ B.T.U.'s per 100 lb. clinker.

Credit Items

(10) HEAT IN CALORIFIC VALUE OF COAL.—Multiply by percentage of standard coal.

Standard coal=27 per cent.

Calorific value= $12,600 \times 27 = 340,200$ B.T.U.

(11) EXOTHERMIC REACTION.—Obtain the percentage of lime in the clinker from the known percentage of CaCO_3 in the slurry. Multiply by 269.6 for B.T.U. per 100 lb. of clinker from exothermic reaction.

Example.—

$\text{CaCO}_3 = 76.5$. $\text{CaO} = 66.5$.

B.T.U. from exothermic reaction per 100 lb. clinker= 66.5×269.6 .

=17,880 B.T.U.'s per 100 lb. clinker.

(12) HEAT IN ORGANIC MATTER IN RAW MATERIAL.—Assuming this to be peat, the calorific value will be approximately 5,000 B.T.U.'s per lb. of organic matter. For 100 lb. of clinker, $7,930 \times$ percentage of organic matter in slurry=B.T.U. per 100 lb. of clinker.

Example.—

Percentage of organic matter in slurry=1.

=7,930 B.T.U.'s per 100 lb. clinker.

Summary

These twelve items are now collected and totalled in the form of a heat balance from which the heat lost by radiation and convection or otherwise is shown as a balance of heat unaccounted for. The divisor for converting British Thermal Units into percentage of standard coal is 12,600.

HEAT BALANCE.*Debits.*—

Heat expelled in chimney gases from—	B.T.U.	Percentage of Standard Coal
CO_2 ex raw materials	8,366	0.664
H_2O „ „	144,692	11.480
Combustion gases	57,861	4.592
Excess air	3,580	0.284
H_2O in coal moisture	4,296	0.341
CO from incomplete combustion	2,907	0.231
From dust and air moisture	2,560	0.203
Heat required in dissociation of carbonate	91,120	7.232
Heat lost in clinker from cooler	4,700	0.373
<hr/>		
Total heat accounted for	320,082	25.400
Balance—not accounted for	45,928	3.648
<hr/>		
Total	366,010	29.048

Credits.—

Coal calorific value	340,200	27.0
Exothermic reaction	17,880	1.419
Organic matter in slurry	7,930	0.629
<hr/>		
Total	366,019	29.048

CHAPTER XII

WASTE-HEAT BOILERS

THE waste-heat boiler as applied to cement works was developed chiefly in the United States, by reason of the more general use there of the dry process of manufacture with its large surplus of heat in the kiln gases. Installations also exist in dry-process works on the Continent. The first installation on record was in 1902 at the Cayuga Lake Cement Company's plant, but this and several more of the early plants were unsuccessful owing to difficulties with the dust and the absence of fans for providing the increased draught required. There appear to have been three successful plants in 1915, and later waste-heat boilers were beginning to be regarded in the U.S.A. as almost a normal part of a cement works' equipment when operating on the dry process.

The gases from a dry-process kiln seldom, if ever, escape at a temperature lower than 1,200 deg. F., and in these circumstances the waste heat is—or was until a few years ago—in many cases sufficient to provide all the power required for manufacture. This is dependent on the raw materials not being unduly hard and containing very little moisture, so that the heat required for drying is moderate in quantity. In some cases this drying can be done with the waste gases after they have passed through the boilers. The case is not quite so strong under modern conditions, owing to the use of longer kilns resulting in lower coal consumption, and to the development of finer grinding which calls for a much greater consumption of power.

There are some comparatively modern works in the U.S.A. using the wet process, in which waste-heat boilers are understood to provide all the steam required with efficient turbo-generators and electric drives throughout, but it is very doubtful if this object is attained without burning more coal in the kiln than is necessary for clinker production in the best modern practice. In the United Kingdom the policy of manufacturers was that while there might be a case for economy in waste-heat boilers with a dry-process plant, there really should not be sufficient waste heat from a properly controlled wet-process rotary kiln to make a waste-heat boiler practicable.

All installations for the utilisation of waste heat demand special care in the design and operation of the works, owing to steam production being entirely dependent on the operation of the kilns. It is necessary to arrange the plant so that the load is regular and so that stoppages of the kilns (which should, of course, be few) will not prevent the maintenance of full output in other departments. It is generally desirable to have one coal-fired boiler under steam to balance the load and carry on the essential operations during kiln stoppages.

There has been much controversy on the relative merits of the unit system (one kiln, one boiler) and a system involving a connecting flue which acts as a collector for the gases from all the kilns and a distributor to the boilers. The latter arrangement undoubtedly affords greater flexibility, but some additional loss of heat is inevitable, and in many cases the cost of the flues and the necessary connections and dampers appears to be excessive in relation to that of the boilers themselves. Such flues require careful designing in order to provide adequate passages for the hot gases, and at the same time to minimise loss of heat through the flue walls. In most plants there is an external steel casing, with a layer of insulating bricks

between it and the fire-brick lining. At a works visited in 1921 it was stated that the loss of temperature between the kilns and boilers was only 20 deg. F. In this installation the connecting flue, which was common to all the kilns, was particularly elaborate, and the loss of heat appeared to be remarkably small—a result obtained only with the most careful design and construction.

Where the unit system is adopted, a by-pass is desirable to maintain continuous kiln operation in the event of the boiler having to be shut down. The omission of a by-pass may cause considerable inconvenience, but if it is provided the unit system has advantages on account of its simplicity, and consequently lower capital cost, as well as the greater efficiency due to lower heat loss in the connecting flues.

In the early days of the waste-heat boiler there appears to have been a tendency to burn excessive coal in the kiln in order to increase the steam production. At one time it was even the practice at some plants to adjust the air supply to the kilns so as to produce about 5 per cent. of carbon monoxide in the gases. With kilns working on the dry process the temperature at the back end was high enough to cause combustion of the carbon monoxide when additional air was admitted between the kiln and the boiler, thus further raising the temperature of the gases at this point. In some cases these practices were probably necessitated by the fact that old-fashioned power plant was still being used, and they became unnecessary as this was replaced by modern turbines with lower steam consumption. The use of excessive coal in the kiln in order to make steam is, of course, misleading as regards the coal consumption for burning only, but it does not necessarily follow that the practice is really wasteful. If the coal supply fed to the kiln were reduced the steam thus lost would have to be made up from separately fired boilers. Now it is recognised that in the rotary kiln the combustion of the coal takes place under the best conditions, enabling the operator to avoid producing carbon monoxide while using a minimum of excess air. A boiler is not so favourably situated in this respect. The combination of the rotary kiln and waste-heat boiler might therefore be considered as providing good conditions for combustion, with boilers entirely removed from the furnace and therefore subject to a minimum of deterioration. Each case must be considered on its merits, and when the total fuel for both burning and power is considered there may be cases where the combination appears attractive, even if more coal is burnt in the kiln than is necessary for clinker production only.

The question of dust requires special consideration, and it is the practice to fit steam jets to remove dust from the heating surface at least once a day. In some cases fixed jets were originally provided, but they resulted in impingement at definite points, causing local erosion. Portable lances are more satisfactory, and, if suitable openings for their use are provided and the lances intelligently used, no difficulty need be anticipated from dust.

In England the waste-heat boiler has not been generally adopted for many reasons. The chief of these is, no doubt, the almost universal use of the wet process of manufacture. In some older works the arrangement of the plant would have made the application of the system difficult, and the full advantages could not be gained without at the same time installing electric generators with motor drives. Such an installation involves very heavy capital expenditure which might not show an adequate return.

With the temperatures at which the gases were allowed to escape a few years ago, even from wet-process kilns, waste-heat boilers were not an unattractive proposition under suitable conditions, but other factors have arisen. Whereas in the dry process no other use arises for the heat in the gases available after the dissociation

of the calcium carbonate, in the wet process no theoretical limit for fuel economy is reached until the gases are reduced to the boiling point of water. The useful application of this low-grade heat in the kiln presents difficulties, but great developments have taken place in the last few years, and it is now possible in many cases to reduce the temperature of the gases in the kiln to almost as low a figure as can be secured economically in a waste-heat boiler.

In the consideration of the relative cost and advantages of the two methods of utilising the heat many factors are involved. The decision may, however, be

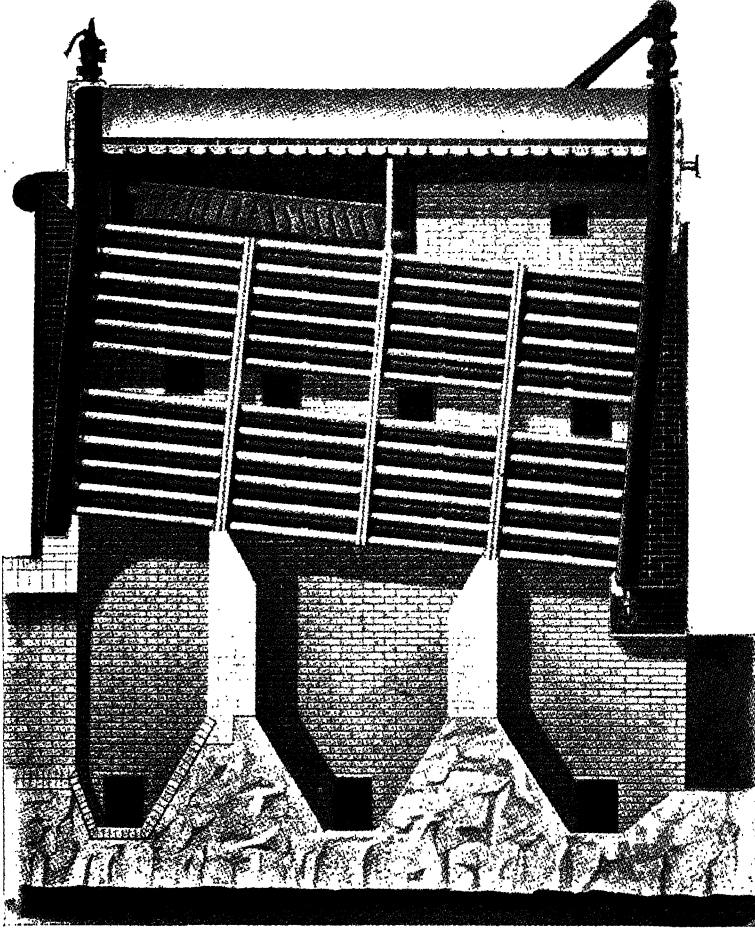


Fig. 124.—Section of Water-Tube Waste-Heat Boiler.

affected by the possibility of purchasing power from outside sources. Only a few years ago it was impossible to buy power at prices comparable with the cost of generation at the works, even with a plant of moderate efficiency, but with the advent of the large power station and long-distance transmission both the cost of power delivered to the works and the security of supply are such that manufacturers can usually avoid the heavy capital expenditure involved in power plants and the trouble of running them.

Boilers installed for the recovery of waste heat may be of the water-tube or gas-tube type. A section through a boiler of the water-tube type is shown in *Fig. 124*,

from which it will be noted that the boiler tubes are baffled to give the gases four passes, thus ensuring a high velocity in passing over the tubes. A typical illustration of this type of boiler in connection with a wet-process plant is given in *Fig. 125*. Two kilns, 11 ft. by 175 ft., with a capacity of 250 tons per day each, were erected in 1926, and a third in 1929. Each of these kilns is equipped with a 900-h.p. four-pass boiler with economisers, superheaters, and fans. This plant provides all the power necessary for manufacturing purposes, including electric shovels and stone crushing. *Fig. 125* shows the first two boilers; the dust chamber can be seen

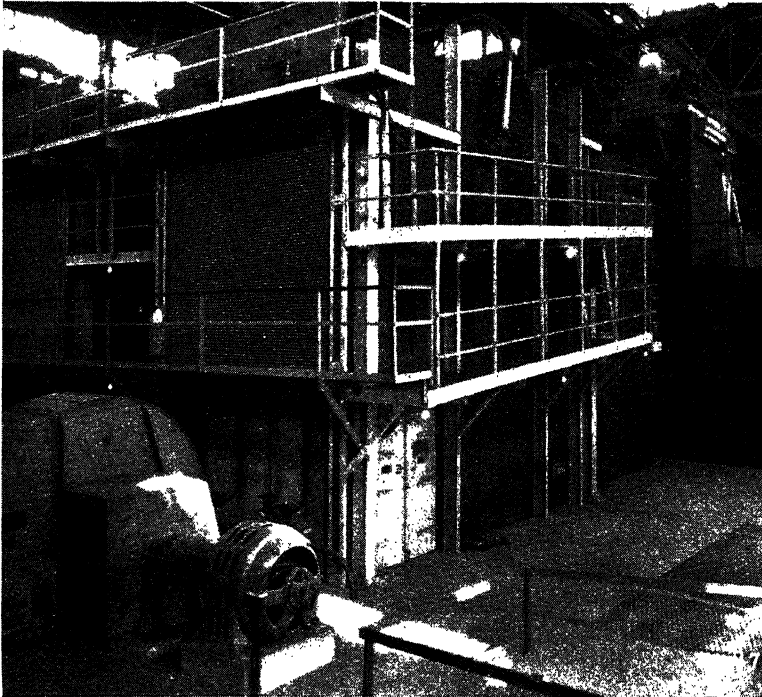


Fig. 125.—Waste-Heat Boilers on Wet-Process Kilns.

between the kiln and boiler. In this case the economiser is placed underneath the fourth pass. On the right is seen a space reserved for the third boiler, which has since been installed.

One of eight 1,000-h.p. waste-heat boilers with economisers, superheaters, and fans generating steam from the waste gases of kilns which produce 1,300 tons of cement a day is shown in *Fig. 126*; a further plant, consisting of two 11 ft. by 200 ft. kilns, producing 800 tons a day, has been added. The last two kilns were equipped with three 1,500-h.p. waste-heat boilers with economisers, any two of which are sufficient to make full use of the waste gases. The eleven waste-heat boilers on these two combined works are the only source of steam available, with a power plant which supplies all power necessary for mining and other departments as well as for the actual manufacture. *Fig. 126* shows the arrangement of these boilers with the shutters open, giving access to the tube caps, and *Fig. 127* shows the economisers and fans.

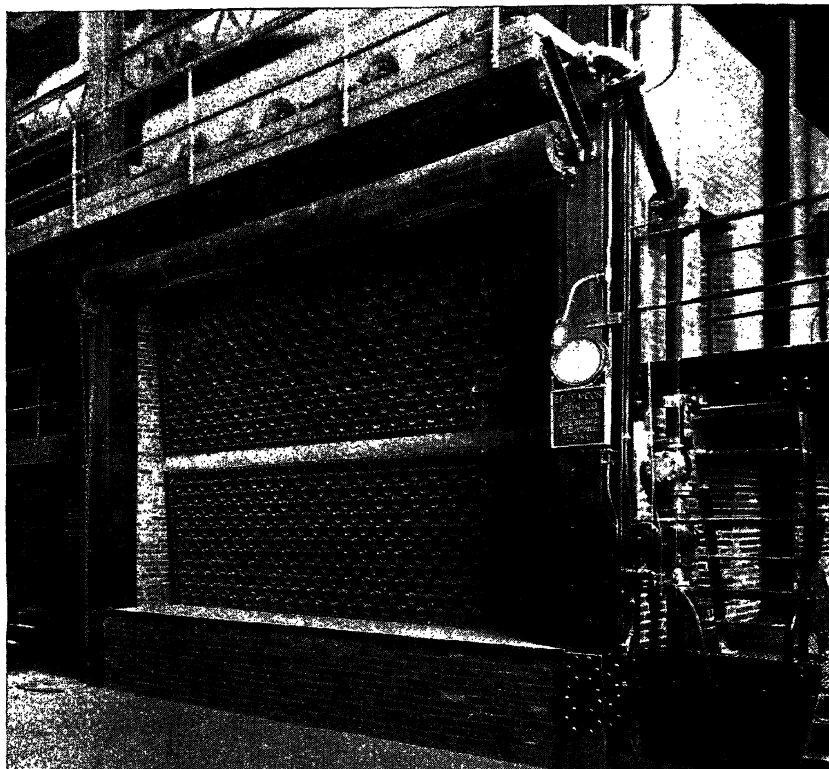


Fig. 126.—Waste-Heat Boiler.



Fig. 127.—Economisers and Fans of Waste-Heat Boilers.

For small installations the gas-tube boiler has some advantages over the water-tube type, the chief being the substantially lower cost due to the simpler setting and the absence of infiltration of air around the boiler heating surface. Difficulties arise, however, with large units on account of the shell thickness required. *Fig. 128* shows a section of an experimental gas-tube boiler at one of the works of the Associated Portland Cement Manufacturers, Ltd., installed in connection with a small kiln then running, which produced $3\frac{1}{2}$ to 4 tons of clinker per hour with slurry containing 42 per cent. of moisture. The simplicity of the arrangement is noticeable, and this comparatively small unit proved satisfactory and economical. During starting moisture was condensed from the gases in the tubes, which collected the dust and formed cakes, but this trouble was eliminated by bringing the water in the

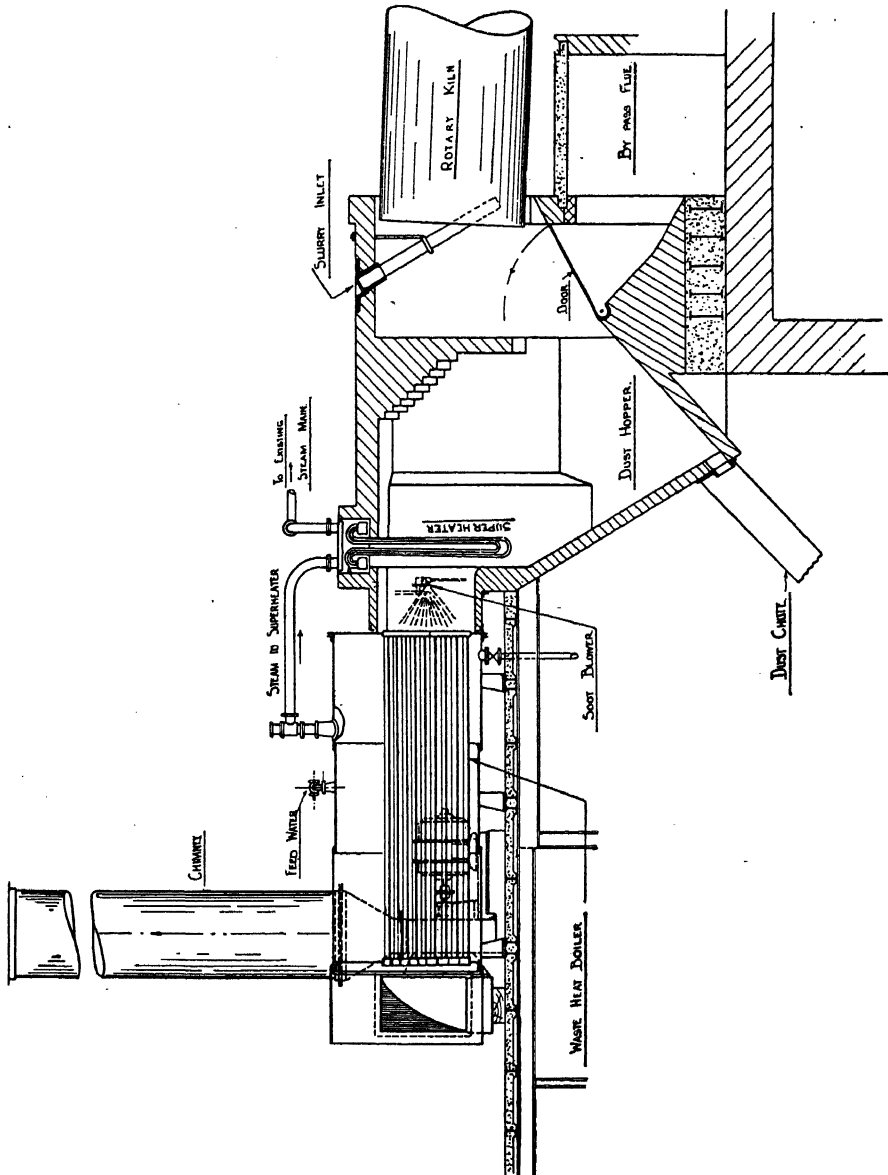


Fig. 128.—Sectional View of Gas-tube Waste-Heat Boiler.

boiler to a temperature slightly over boiling by means of steam from other boilers before the waste gases were passed through the tubes. After this precaution no other trouble was experienced with dust, which was blown out of the tubes periodically by steam jets carried on a swivelling pipe. An elaborate series of tests was carried out on this installation, and over a period of eleven weeks with an average gas temperature of 758 deg. F. at the superheater inlet the average evaporation was 985 lb. of steam per ton of clinker at a pressure of 130 lb. per square inch and a temperature of 485 deg. F.

The laws governing the transfer of heat in such gas tubes were very fully investigated by Lowford H. Fry, and the results of his investigation are given in a paper read before the American Society of Mechanical Engineers, December 1917. The tests made on the boiler described fully confirmed the accuracy of Fry's Law.

CHAPTER XIV

COAL GRINDING

IN an earlier chapter the crushing machinery necessary in the preliminary stages of cement manufacture was classified according to type, and the distinguishing features of each type of crusher were discussed. It is now proposed to deal at some length with the grinding of the fuel for rotary kilns, especially the unit system of pulverisation. The various problems involved and machinery used in the other stages of reduction in cement factories will be dealt with later.

The subject of the use of pulverised fuel has become prominent in recent years in connection with steam-raising plants, and it is interesting to note that it was in this direction that the first recorded application of powdered fuel was made by Crampton in 1875. For many years, however, little or no progress was made in connection with boilers, and almost all the early developments took place in connection with the cement industry. More than $1\frac{1}{2}$ million tons of coal are now pulverised every year in the United Kingdom for cement manufacture alone.

The need for economy, both in the fuel and in labour, has brought with it the realisation that to cheapen any process in which coal is used it is essential to have complete control of combustion conditions if the maximum thermal efficiency is to be obtained. Pulverised coal readily makes this possible, being somewhat similar in nature to oil or gas. The wider application of pulverised fuel has naturally led to a good deal of development, and a considerable amount of experimental work has been done in the United States and on the Continent as well as in England.

Unit Pulverisers

The unit system of pulverisation for rotary kilns in which each kiln is equipped with plant working in direct conjunction with it appears to have been developed more particularly in England. Reference to this has already been made in the chapter on rotary kilns, but the subject will now be more fully developed and some historical facts may be interesting, reference to the older systems being necessary in order to explain the advantages of later developments.

As often happens when an industry is called upon to develop some new process, the machines which are evolved follow closely those with which that industry is familiar. This happened in the case of pulverising coal for the early rotary kilns, when cement manufacturers used the same type of mills as they had previously used for grinding cement, with all the accessories such as screws, elevators, etc. These ideas were perpetuated in later plants with possibly further additions, until the complicated central or bin-and-feeder system had become general. In the simplest form of this system, after leaving the raw coal store hopper (which is common to any system) the coal must pass through the following processes before it emerges as pulverised coal at the burner :

- (1) The removal of free moisture by passing it through some form of dryer.
- (2) The conveying and possibly the elevating of the dry raw coal to the dry raw coal hopper.
- (3) The extraction of the dry coal and feeding it to the grinding plant.
- (4) Grinding.

(5) The conveying and possibly the elevating of the pulverised coal to the finished coal hopper.

(6) The extraction from the finished coal hopper and feeding into the primary air supply.

This is a rather formidable list, but in practice the coal is sometimes handled an even greater number of times and, of course, requires the use of additional elevators, conveyors, etc. A consideration of these various processes in detail brings to light many difficulties, of which it may be useful to mention the following.

(1) The reduction of the moisture in raw coal to a suitable value is not as easy as it would appear. Moisture occurs in two forms, generally known as "free," and "inherent" or hygroscopic. The former is that which is given up by the coal when exposed to warm air at ordinary temperature. The latter is not affected even by prolonged exposure. The inherent moisture in a coal may be high, but it will not appear wet to the touch. It is the free moisture which causes trouble in the pulverising system, and this is particularly the case when there is any concentration due to drainage or condensation. Various forms of dryers are used, the heat for which may be provided by furnaces of various types, waste heat in the form of air or gases, or steam. Opinions differ as to the allowable percentage of free moisture in the dried coal. One per cent. is frequently spoken of, and even specified in contracts, but from 3 to 4 per cent. more usually remains after drying even in a well-designed plant carefully operated. Dryers undoubtedly form the weakest and most troublesome link in the chain of operations carried out in connection with the coal in the older systems, and corrosion is especially active in this part of the plant owing to the acid nature of the moisture released during the heating process. The maintenance of dryers therefore becomes a heavy item after the first few years.

(2) and (5) Conveying and elevating do not present any particular difficulty beyond the question of maintenance, which is a substantial item, and loss of fuel in the form of dust.

(3) The extraction of the so-called dry coal often causes considerable difficulty owing to sweating during storage. When this happens the coal "packs," rendering the feed to the grinding plant very irregular. This in turn results in trouble on the grinding plant, and with some types of mill may cause mechanical breakdown.

(4) The grinding process does not call for any comment here, as the problem as a whole is dealt with later in reference to the unit system.

(6) The regular feeding of the pulverised coal to the primary air presents much greater difficulty than is generally supposed. Various forms of feeder, such as single, twin, and variable-pitch screws, have been designed, and are extensively used, but most of them lack the essential feature of providing an absolutely regular feed under varying conditions of rate of feed and condition of the coal. These irregularities cause what is known as "flushing," and are responsible for temporarily bad combustion. The storage of fine coal also introduces the fire hazard. Once the coal "heats" it is very difficult, if not impossible, to put the fire out, and generally the hopper has to be emptied. Systems needing so much mechanical handling of the coal inevitably involve loss and trouble with dust, and it is a matter of no little difficulty to reduce the loss of coal to a negligible amount and keep the surrounding buildings and plant reasonably clean.

The unit system of coal pulverising and direct firing do away with all the disadvantages of the separate drying, grinding, and storage system, as the raw coal is drawn from the store only as it is needed and within a few moments is dried, pulverised, and blown into the furnace where it is consumed. These operations are

carried out in one group of machines, consisting simply of a mill and fan with the addition in some cases of a classifier. In some of the units the fan is fitted as an integral part of the pulveriser. No separate dryer is necessary even with coal containing as much as 15 per cent. of moisture, as owing to the coal and air being thoroughly mixed during the process of pulverisation, and the fact that at no stage is there any storage, the moisture does not have any opportunity of causing the coal to "pack." It is an essential feature of all successful unit pulverisers that the coal be brought into intimate contact with a substantial proportion of the air required for combustion during the pulverising or selective operations, and that this air should be hot—in most cases it is available from the clinker cooler.

Thus, in all types of unit pulverising plants air is used as the conveying medium for the coal, at least during part of the process, and because of this, very small differences in the shape and proportion of parts produce widely varying results. In a general way, all sudden changes in direction of flow should be avoided, velocities should be kept as low as is consistent with the proper carrying of the coal, and projections in the path of the air should be carefully avoided as they cause eddies which, in turn, cause both the projecting and the surrounding parts to wear away rapidly. For instance, a plate in a certain position may after long service show little or no wear, but if for any reason a bolt head is fixed on the same plate, wear will rapidly take place both on the head and on the plate around it. Even counter-sinking does not solve the trouble; it is far better to present a smooth and unbroken surface to the flow of dust-laden air. These remarks apply particularly to fans in which the air contains pulverised coal, but they also apply to other parts of the plants, such as classifiers.

Resistance of Materials to Abrasion

Opinions differ considerably as to the best materials to use for resisting wear due to abrasion. There is, however, a considerable amount of evidence both in this country and abroad to show that the hardest material, that is, the material which gives the highest Brinell figure, does not necessarily give the best all-round results. Manganese, chrome, chrome nickel, nickel, and other alloy steels have been used as well as chilled cast iron, high carbon steel, and ordinary boiler plate, and the last has frequently been found to give the best results, taking into consideration the first cost. Stellite has been tried, but the high cost has hitherto restricted its use.

The rate and nature of the wear in the mill or pulveriser, separator, and fan also vary widely with the nature of the coal. It does not necessarily follow that because a coal contains a high percentage of ash the rate of wear will be high. More often the nature of the ash is the determining factor. Some coals contain more matter of an abrasive nature in the ash than others; for instance, a high proportion of iron pyrites will almost certainly cause excessive rate of wear. The rate of wear, as in other kinds of machinery, is generally greater where a high peripheral speed is adopted. This is true with the high-speed type of pulveriser, and under certain conditions the rate of wear may be considerable, but in most designs the parts affected can be quickly and relatively cheaply renewed.

A certain amount of experimental work has been carried out in America and in England with rubber-coated impeller blades and fan-case linings, but although rubber possesses the property of resisting abrasion under some conditions there is considerable difficulty in obtaining the requisite cohesion between the rubber and metal. This is particularly noticeable when the rotating parts are running at high speed and the temperature is 150 deg. F. or over.

Conditions of Grinding

The nature of coals to be pulverised varies over a wide range, and results obtained on one class cannot necessarily be repeated with a different quality. In general it is probable that British coals are harder than American and Continental, omitting the anthracites, which are little used in cement manufacture. This necessitates care in the design and proportions of the plants for use with British coals. Machines which have given entire satisfaction on soft coals have failed to fulfil their guarantees both as regards output and wear-resisting qualities when used for pulverising relatively hard British coals.

The conditions imposed upon a pulverising plant are often determined by the ultimate use of the pulverised coal. For instance, a plant for firing a boiler is generally required to operate with the minimum of primary air, 15 per cent. of the total air for combustion being a very usual figure. In the case of a rotary kiln, there are plants in operation using as little as 6 per cent. of the total air as primary air, but this is far too low. On modern plants the primary air averages about 30 per cent. of the total air required. It is generally not less than 25 per cent. and may be as high as 45 per cent. Conditions so widely different as these naturally present two independent problems, but frequently one design of machine is expected to satisfy both.

Conditions at the burner also vary considerably. In the case of the boiler plant a low velocity of air with as much turbulence as possible is generally required in order to produce a short flame, whereas with the rotary kiln a much higher velocity and longer flame are frequently desirable. In the former case velocities of about 50 linear feet per second or less are usual, but for rotary kilns up to 275 linear feet per second have been used, although a more usual figure is from 150 to 200 linear feet per second. Velocities of the order required for rotary kiln burning, therefore, necessitate considerable additional dynamic pressures being developed in the fan, and this increases wear and tear as well as resulting in greater power consumption. These additions are not for the improvement of pulverisation, and their justification comes from the consequent economies in kiln operation.

There is still considerable difference of opinion among those responsible for the operation of rotary kilns as to the most economical conditions of burning. Recent opinion is tending towards feeding a large proportion of the total air required for combustion through the burner with the coal, even at the expense of increased fan power. There remains, however, the question of burner velocity. Low air velocity, even with a fixed quantity of air, means relatively small fan-power combined with a short flame, and it is probable that with a suitable kiln design this is economical. Kilns having integral coolers call for relatively long burners. Such a feature involves considerable practical difficulties and in consequence there is a tendency to shorten the burner-pipe and increase the velocity to compensate for it, so as to produce a flame in a suitable position. This has the dual effect of reducing the length of burner-pipe exposed to radiant heat from the hot clinker, and of carrying away the heat radiated from the clinker on to the burner more rapidly by the high air velocity, but this has to be paid for in power consumed by the fan. A considerable variety of practice in this matter seems likely to persist owing to the various proportions of kilns and the variety of raw materials and fuel; the personal factor also counts for much in the operation of rotary kilns.

The point which emerges from these considerations is that unit coal pulverisers cannot be designed without regard to the kilns with which they are intended to

operate. The plant for, and the cost of, pulverising and delivery to the kilns will depend very largely on the burning operation, as distinct from the pulverising operation, the power consumed in the fan and the cost of wear and tear in this unit particularly being affected by burning conditions.

Types of Mill

Unit pulverisers may be conveniently classified according to the means of pulverisation employed, namely, impact, crushing, and attrition. There are many types of mill which come under each of these main headings, and some which may be said to combine two of the methods of reduction. In all types of mill working on the unit system with direct firing, air is used as a carrying and classifying medium. In some systems the coal is classified in the mill itself, but in others this is done externally in a separate classifying unit.

Before describing in detail the various plants available, it is perhaps desirable to consider under which class the main types of mill come.

IMPACT.—True impact mills are the hammer or paddle mill. Ball-and-tube mills may also be placed under this heading, though they combine both impact and attrition.

CRUSHING.—Roll mills reduce the material by crushing with perhaps a small amount of attrition. Most mills under this heading use a ring in conjunction with the rolls.

ATTRITION.—The mills which depend on attrition only are the burr stones of the early days of milling and cement making (*Fig. 145*), and the disk mills used for preparing very fine food powder and colours, but none of these is satisfactory for pulverising coal, owing to their limited capacity and excessive rate of wear, and they are therefore not dealt with here.

IMPACT MILLS.—The following are some typical examples of mills in this class :—

(1) "Resolutor"; (2) "Atritor"; (3) "Bettington"; (4) air-swept ball or tube mill; (5) ball or tube mill with sifter system.

(1) The "Resolutor" pulveriser (*Figs. 129-131*) is of the paddle type, air-swept, and has combined with it a fan and separator. The plant operates as follows: Coal from the raw store enters the feed hopper at (A), from which it is taken by the totally-enclosed feed band (B) into the chute (C). The coal, as it passes over the end of the chute (C), is met by an upward current of hot air, the velocity of which can be varied by the adjustable vane (D). The velocity of the air is regulated so that the coal is lifted over the vane (D) and into the pulverising chamber (E). If any foreign matter of a higher specific gravity, such as tramp iron, is mixed with the coal, the air velocity is insufficient to lift it over the vane (D) and it falls down the air passage against the air stream through an automatic door to the outside of the machine. The rough coal as it enters the pulveriser chamber is thrown by centrifugal force from the paddles (F) against the special chrome-steel lining plates of the pulverising chamber (G). The bombardment of coal against the lining plates goes on until the pieces are sufficiently reduced in size to be carried forward by the air entering at (H) and induced through the system by the fan (I). The fine and less-fine coal is carried by the air up the duct (J), which decreases in cross-sectional area at the top, and is ultimately deflected by the curved plate (K) in a slightly downward direction; at the same time the air is allowed suddenly to expand. The coal which is sufficiently fine passes out with the air through the pipe (L) to the fan (I) and thus to the burner. The less-fine coal drops to the bottom of the expansion chamber or separator, and is delivered back to the machine by the ducts (M) for

further pulverising. As with most high-speed pulverisers, the wear on the paddles of the wheel and the lining is relatively rapid, but this varies considerably with different classes of coal. Provision is, however, made for quickly renewing these parts.

On machines up to about 3 tons per hour capacity the paddle wheel revolves

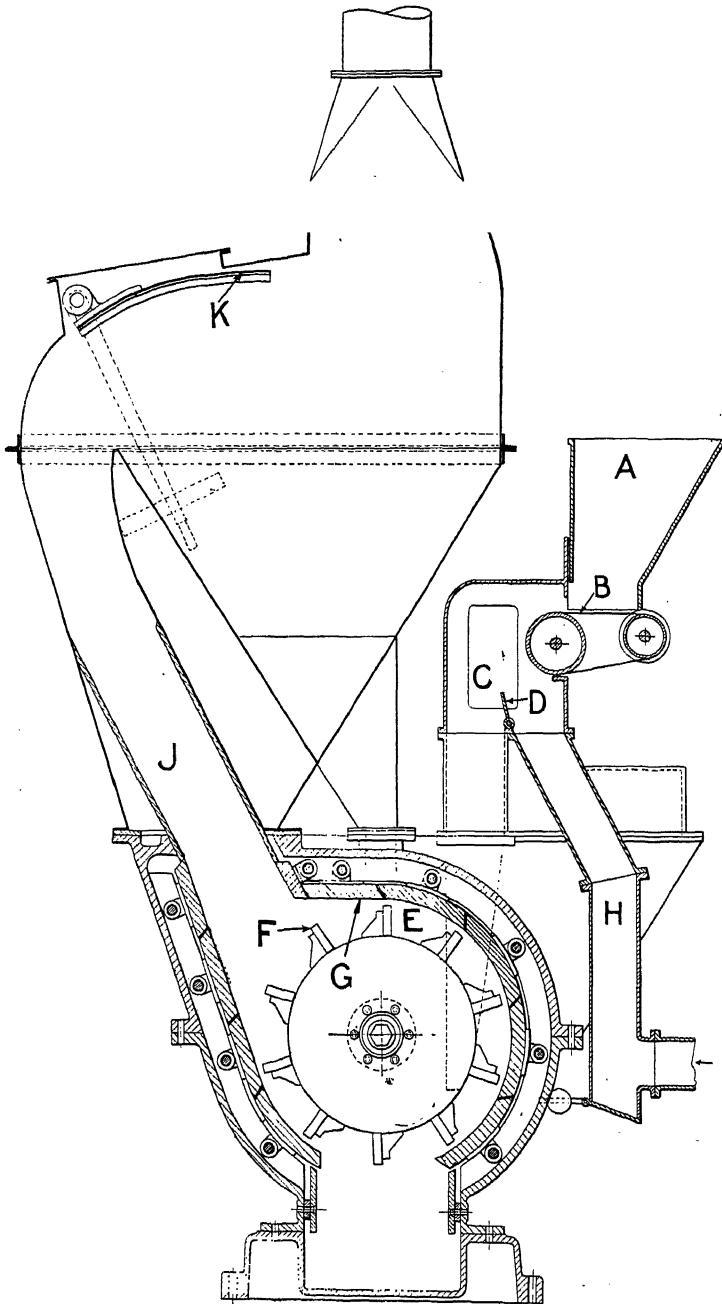


Fig. 129.—Cross Section of "Resolutor" Pulveriser.

at a speed up to 1,450 r.p.m., but for capacities above this speeds of 1,000 r.p.m. or below are used. To meet the definite speeds imposed by the frequency of alternating current supplies, the diameter of the paddle wheel and of the chamber lining can be varied within certain limits.

It is not possible to give any representative information regarding power consumption and fineness, as with all types of coal-grinding plant these performances

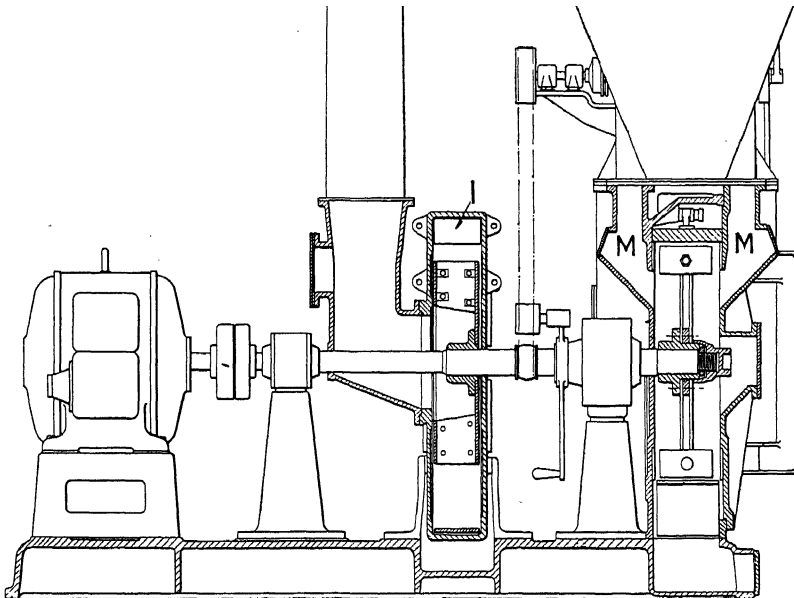
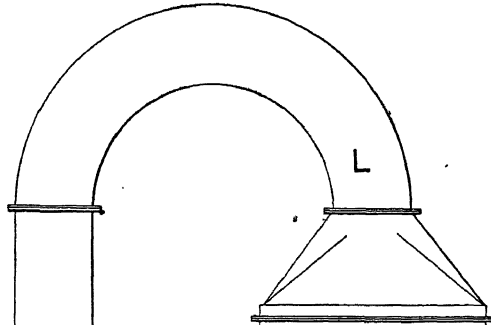


Fig. 130.—End Section of "Resolutor" Pulveriser.

vary considerably with different classes of coal and with the moisture content. As an example, however, the following figures relate to a machine operating on Kent coal, which is very soft and readily pulverised. Power: 15 kW. hours per ton of coal pulverised; fineness: 22 per cent. residue on the 170-mesh sieve, 7 per cent. on the 100-mesh sieve, and 0.8 per cent. on the 72-mesh sieve; moisture: 6 per cent.

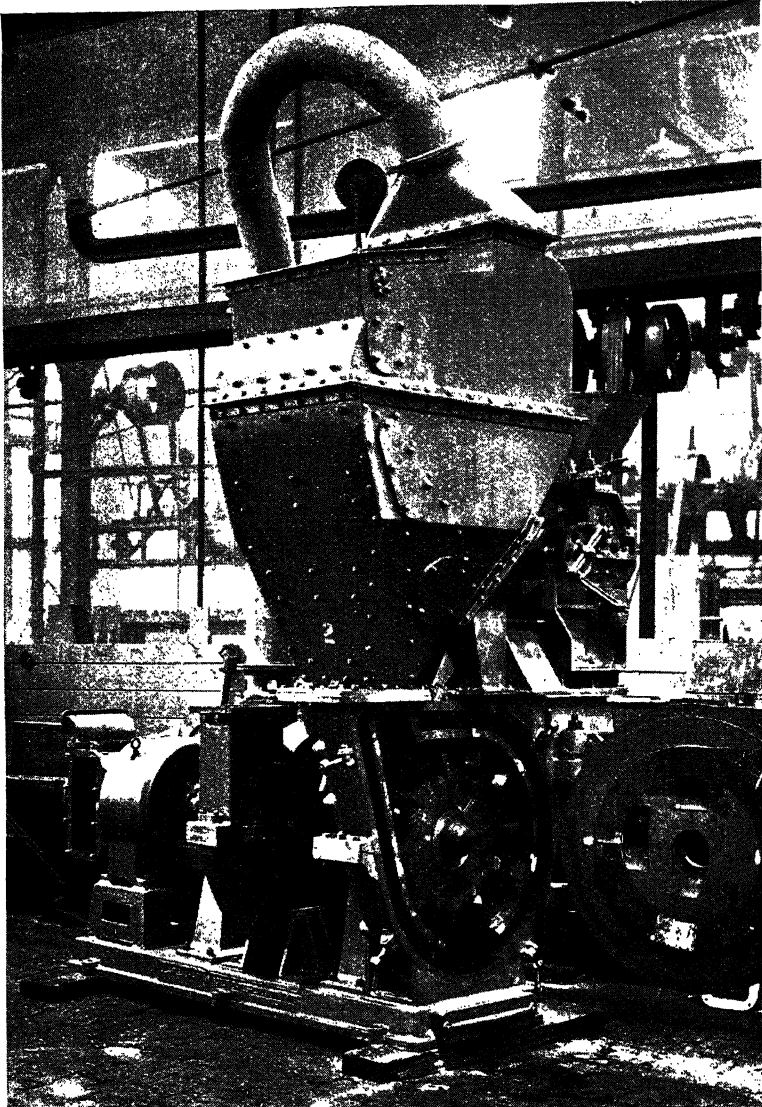


Fig. 131.—“ Resolutor ” Pulveriser.

(2) The “ Atritor ” mill (*Figs. 132 and 133*) pulverises in two stages; the first depends on impact and the second on attrition and impact. In the first stage swinging hammers are employed, and in the second the coal is driven by pegs fitted to the face of a rotating disk, called the rotor, against similar pegs fitted to a fixed disk known as the stator. Both pulverising stages are air-swept by an integral fan.

The velocity of the air is such that only coal which is sufficiently fine for passing to the burner is carried away, and therefore no separator is employed.

Referring to *Fig. 133*, coal from the storage hopper enters a small feed hopper above the table feeder (A) from which the coal falls in a stream, divided by the adjustable vane (B) into two passages situated on either side of the centre line of the machine. At (C) the coal, which is falling by gravity, meets an air current which is ascending the duct (D). The velocity of this air is sufficient to bring the coal of $\frac{3}{4}$ -in. to $\frac{1}{2}$ -in. cube to rest and start it in the same direction as the air stream. The mixture of coal and air enters the first stage of the pulveriser at (E). Any material which is of greater density than coal is not carried into the machine, but

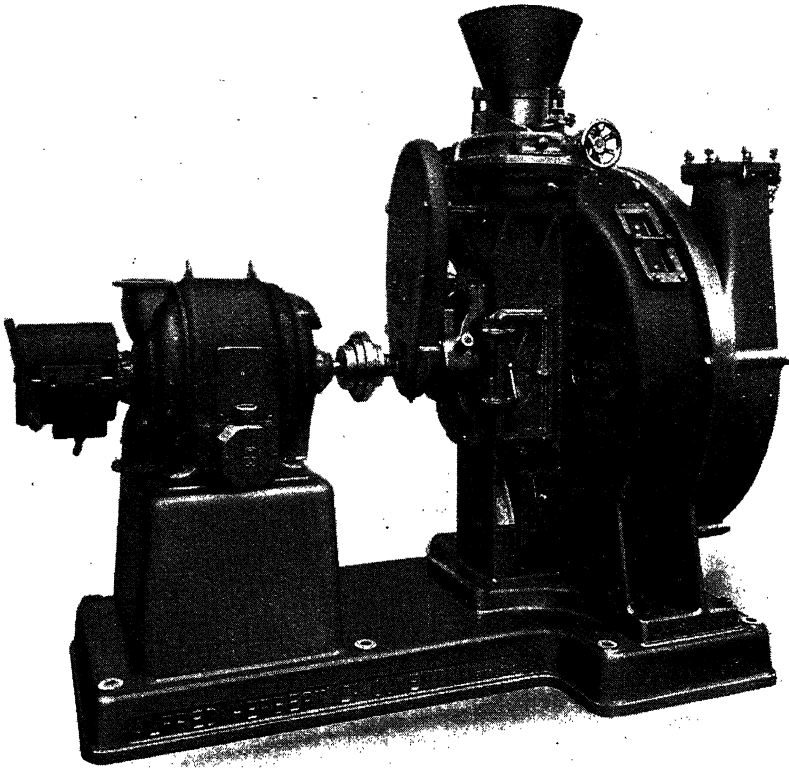


Fig. 132.—“Atritor” Mill.

continues to fall against the air stream down the duct (D), and eventually outside the machine.

In the first pulverising stage the coal is thrown out by the swinging hammers (F) against the perforated circumferential plate (G). These plates do not entirely surround the chamber, as a segment is omitted at the bottom. As the coal becomes sufficiently fine it is carried by the air current induced by the fan (H) over the edge of the rotor (I) into the second pulverising stage. The partly-pulverised coal is then drawn by the current of air between the pegs on the stator and rotor, which reduce it still further, so that by the time it reaches the centre of the rotor it is sufficiently fine to pass out at (J) with the air to the fan. The inducing of the coal by the air

current towards the centre of the rotor against its own centrifugal action plays an important part in the finer pulverising of the coal, as considerable eddies are set up and the coal particles are made to impinge against one another as well as against the pegs on the rotor and stator. The pulverised coal with its carrying air leaves the machine at (K) and proceeds by suitable ducts to the burner. In addition to the air entering by the duct (D) a further quantity, preferably hot, can be admitted by the damper (L). This air passes through a perforated plate in the side of the first pulverising chamber where it mixes with the primary air and coal. The hot air is for the purpose of drying the coal and preventing condensation in the machine. If

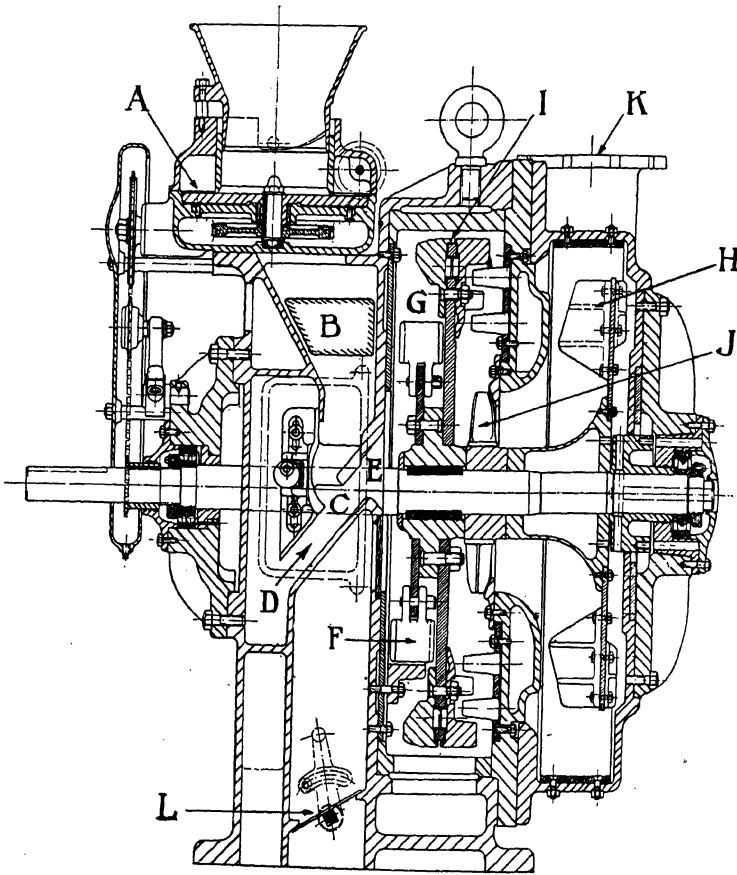


Fig. 133.—Sectional Elevation of "Atritor" Mill.

a still larger quantity of air is needed to pass with the coal to the burners this may be admitted through the end cover of the fan. By this means the velocity of air through the machine (which naturally must be kept between certain limits) is not affected.

The swinging hammers and circumferential plates of the first stage are made of manganese steel. In the second stage the lining plates are of cast iron, which is also employed for the stator and rotor pegs. In some of the more recent types of machines, the pegs are replaced by cast-iron segmental blocks, with a number of square pegs set on the face of each. Access to the inside of the machine is obtained

by a door forming the outer end cover of the fan through which the whole of the wearing parts can be withdrawn and replaced.

The power taken naturally varies with different classes of coal, but with average hard coal and with the fan delivering 25 per cent. to 30 per cent. of the total air against 4-in. water-gauge static pressure, it is about 16 to 17 kW. hours per ton of coal pulverised. A machine of this type used for firing a rotary kiln satisfactorily deals with a coal containing up to 15 per cent. moisture and grinds it to the following fineness: Residue on 170-mesh sieve, 16 to 18 per cent.; residue on 100-mesh sieve, 6 to 8 per cent.; residue on 72-mesh sieve, 1.5 per cent. The cost of repairs, the makers state, should not exceed threepence per ton, and on the plant to which the above figures relate the cost is said to be about twopence per ton of coal pulverised.

The foregoing machines have been described at some length, as they are perhaps the most developed of their type in this country. They also represent the two main types of unit pulverisers which work by impact. The "Resolutor" depends for the fineness of the finished coal on the use of the separator, whereas the "Atritor" has no separator and is entirely dependent on the velocity of the air through the machine. The "Bettington" pulveriser in its latest form is similar to the "Atritor," except that only swinging hammers are employed and the machine is of more simple construction.

AIR-SWEPT BALL OR TUBE MILLS.—The application of hot-air sweeping to pulverisers raised the question whether this system was not equally applicable to combination ball-and-tube mills, and experiments quickly decided this point in the affirmative. The air-swept tube mill is similar in construction to the ordinary ball-and-tube mill, with the exception that the trunnion bearings are of somewhat larger diameter than is necessary in the standard mill. The distinguishing characteristic of the air-swept mill is that the fine material after grinding is not lifted out of the mill by mechanical means or allowed to flow out by gravity, but is swept out by a hot-air current of suitable velocity. Like the impact mills, air-swept tube mills have found their greatest sphere of usefulness in the grinding of damp coal without the aid of a separate dryer, and their reliability and low repair costs have brought about a considerable extension of their use during recent years. Installations of air-swept tube-mills vary considerably in detail. In the simplest form a two-compartment mill is provided, one compartment being fitted with stepped linings and a charge of 3-in. balls and the second compartment having a similar lining with 1-in. or smaller cast-iron grinding bodies. A vertical uptake pipe from the exit end of the mill joins directly to the suction side of the firing fan, the pressure side of which terminates in a pipe leading to the burning nozzle of the kiln. The intake of the mills, in addition to receiving the regulated coal supply, is extended in the form of a pipe connecting to a source of hot air. In the case of rotary kilns this is usually the hot-air chamber connecting the kiln with the clinker cooler. The vertical outlet pipe acts as a classifier because of the velocity of air drawn up through it. The heavier coal particles which may have been swept out of the mill drop back and re-enter the outlet trunnion for further grinding.

Another arrangement of this mill is to connect the outlet trunnion to an air separator or classifying cyclone which extracts the grits and returns them to the intake of the mill for further grinding. The fine coal, after this separation, is then conveyed through the fan to the burning nozzle for firing.

A third method is to provide a cyclone for settling the fine coal which is passed into storage for burning at a later period. Strictly, this type of plant does not operate as either a direct-firing or a bin-and-feeder system, as only the coal which

is not caught by the cyclone passes by way of the fan direct to the burner: it is therefore a combination of both systems. As a number of plants of this type are operating satisfactorily, the following short description may be found useful. While the plant (*Fig. 134*) necessitates the use of a storage bin for the fine coal combined with extracting gear for delivering to the burner, it has two substantial advantages, namely, it permits the stopping of the mill for repairs, and the mill may be run at

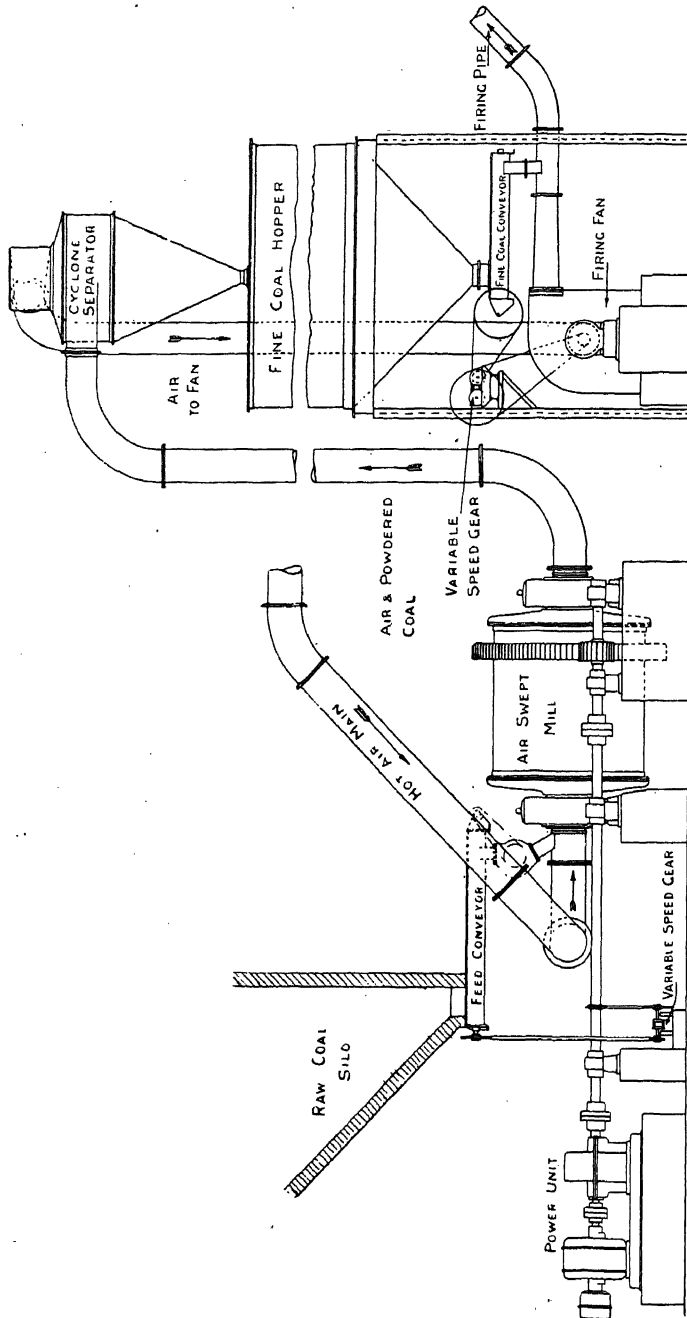


Fig. 134.—Air-swept Tube-mill Plant.

its full economic output irrespective of the quantity of coal required to be burnt from moment to moment, which leads to a saving in power as tube-mills are not economical unless run at full capacity.

Elevating the coal from the mill to the fine storage hopper can be accomplished while the coal particles are in suspension in the air current, and this method tends to simplicity in the arrangement of the plant. Mechanical elevation is, however, more economical in power and fan maintenance, and is less expensive, as a lower suction head is required because there is no need to elevate the coal to any great height. The precise details of the arrangement for an air-swept mill plant will therefore depend upon local conditions.

The ball charge may vary between rather wide limits, and it is characteristic of this type of mill that many varying outputs can be obtained economically without serious alteration of the mill. It may be run with a high charge of balls weighing up to 2 tons of balls for each ton of output per hour, or it may be run as a single-chamber mill with stepped or corrugated linings and a light charge of about one ton of balls per ton of coal per hour.

Output depends to some extent upon the initial amount of water in the coal. Up to 8 per cent. of water has no noticeable effect in reducing the efficiency of the mill, while in extreme cases coal so wet as to form a kind of slurry can be dealt with by these mills, though at some sacrifice in output. In normal working the danger of explosion from the use of air-swept mills is very remote. Mills of this type are running continuously with a stream of red-hot dust particles entering with the hot air. Usually the quantity of coal in suspension is too great to form an explosive mixture, but if by any chance such explosive mixture were formed the result of the firing of the charge would not be serious, as no great pressure could be set up in the system of mill and trunking.

Typical figures for power consumption per ton of coal pulverised by this third method are: Air-swept mill, 21.5 kW. hours; fan, feeder, and auxiliaries, 4.5 kW. hours; total, 26.0 kW. hours.

With the Fuller-Bonnot mill (*Figs. 135 and 136*) two separators are used, one inside the mill for preliminary classification and one outside for final separation. Air and coal enter the mill through the hollow trunnion as in the machine previously described, but before the air can pass out at the other end it must enter the perforated tube or classifier which forms an extension of the hollow outlet trunnion. In doing this the larger particles of coal which are in suspension in the air are rejected and fall back into the mill for further grinding. The finer coal passes on with the air into the exterior separator, where, due to expansion and change of direction, only the finest of the pulverised coal leaves the plant to enter the fan and go to the burner. The speed of the mill is about 30 r.p.m., being rather higher for the 1-ton per hour size and slightly less for the 5-ton per hour size. The power consumption is rather less than in the plain air-swept tube-mill, but the maintenance is rather more due to the addition of separators.

The combination of ball-mill with Rema classifier employs a different principle. The mill is not air-swept, as the necessary drying of the raw coal and the classifying of the pulverised coal are carried out in separate systems, the operation of which is dependent on the use of hot air. Unlike any other grinding system, the raw coal is not fed into the mill but into the hot air stream, which carries the whole of the coal into a separator. There the finest of the coal, which is of a size suitable for immediate use, passes out with the air to the burner. The remainder only is fed to the mill for grinding and is subsequently returned to the air stream to be again passed

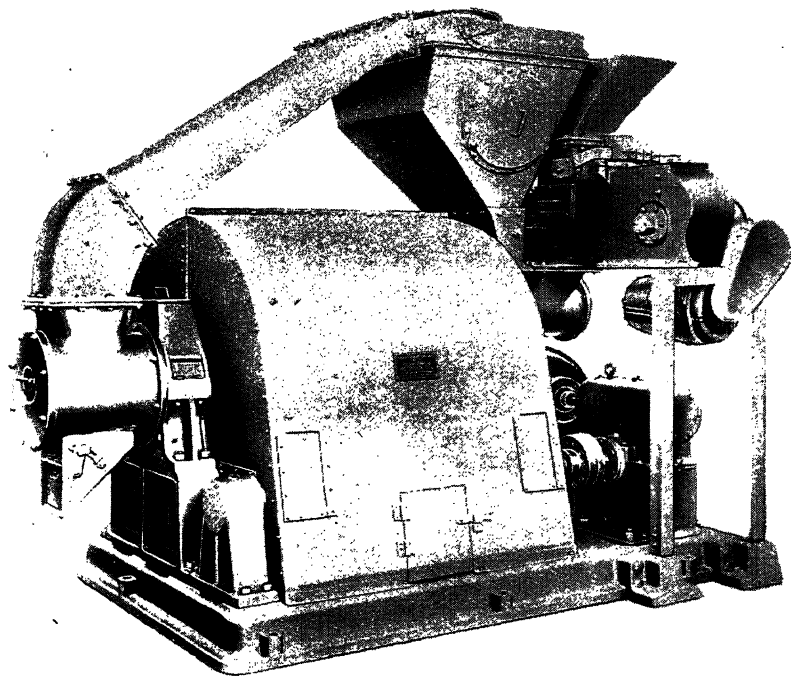


Fig. 135.—Fuller-Bonnot Mill.

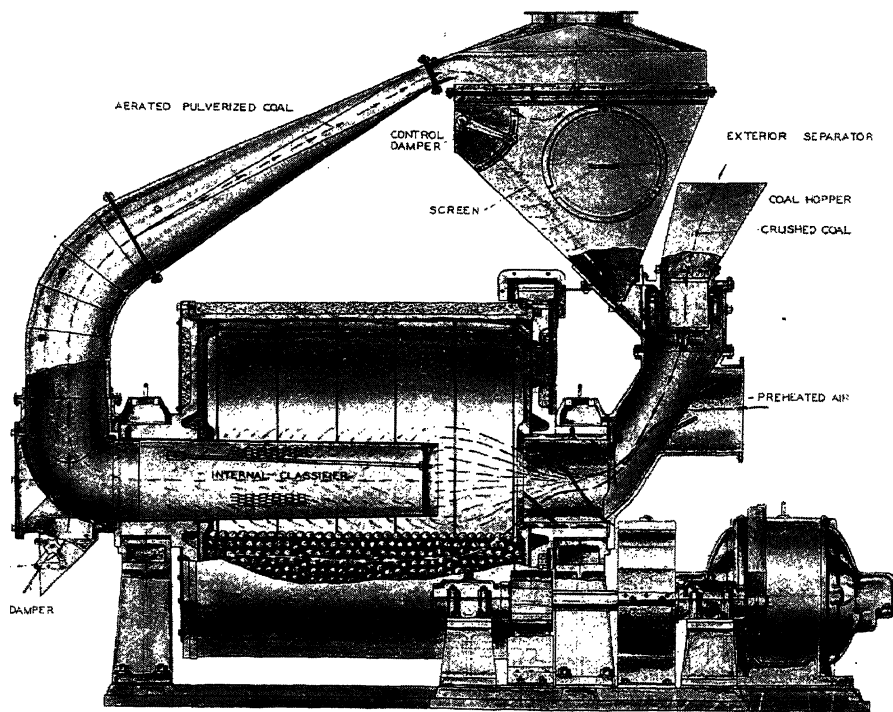


Fig. 136.—Section of Fuller-Bonnot Mill.

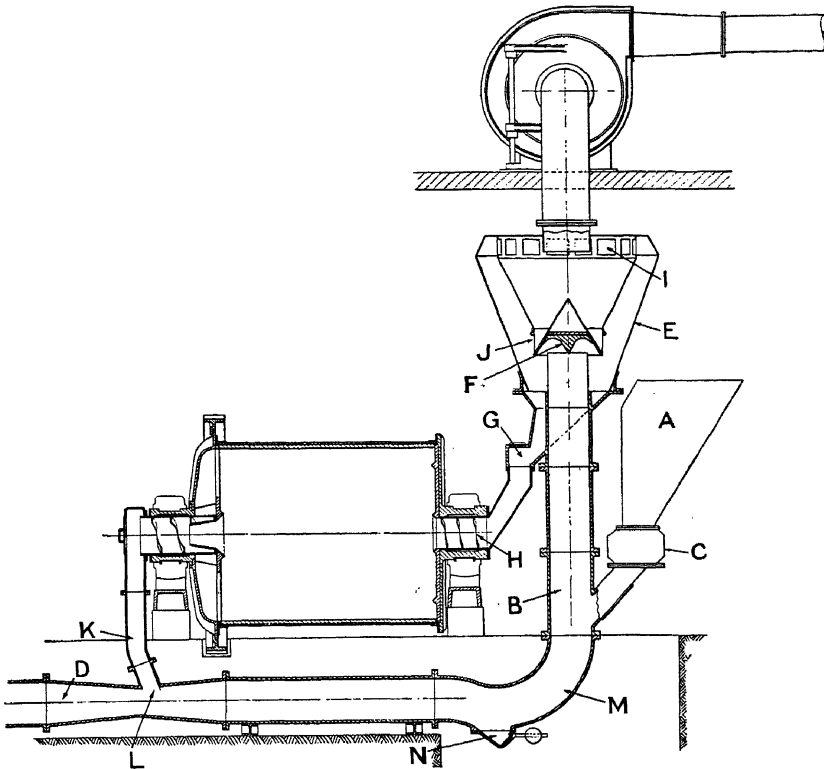


Fig. 137.—Sectional Elevation of Ball-mill with Rema Classifier.

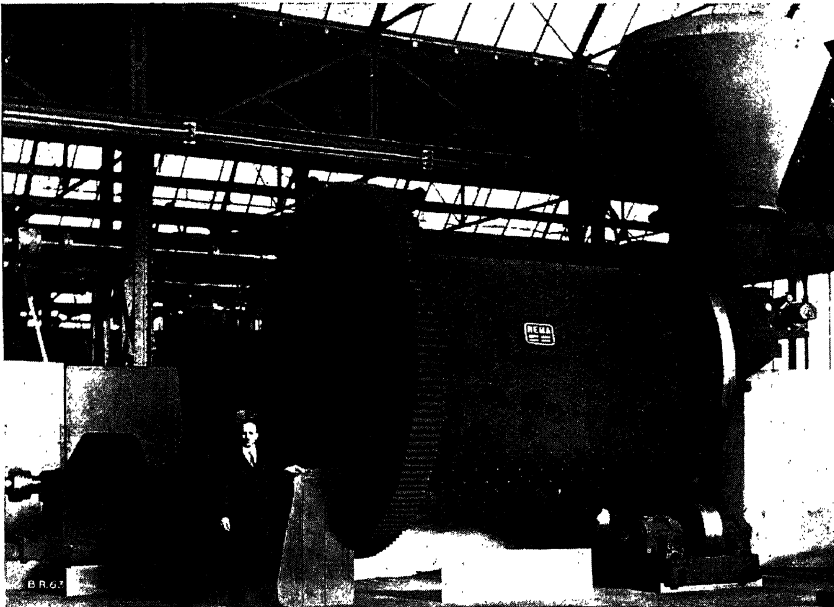


Fig. 138.—Ball-mill for 15 Tons per Hour, with Rema Classifier.

through the separator. The advantages of this system are: (a) The raw coal is brought into very intimate contact with the hot air before it enters the mill and in this way is quickly dried; (b) with certain fine and soft coals the mill has only to grind 85 to 90 per cent. of the total feed, as the remainder is so fine that all of it will pass the 100-mesh sieve and most will pass the 170-mesh sieve; (c) the efficiency of the ball-mill is increased by the fact that only grit and coarse coal are fed into it. This results in a further saving of power.

Several means are employed for mounting these ball-mills. *Fig. 137* shows a

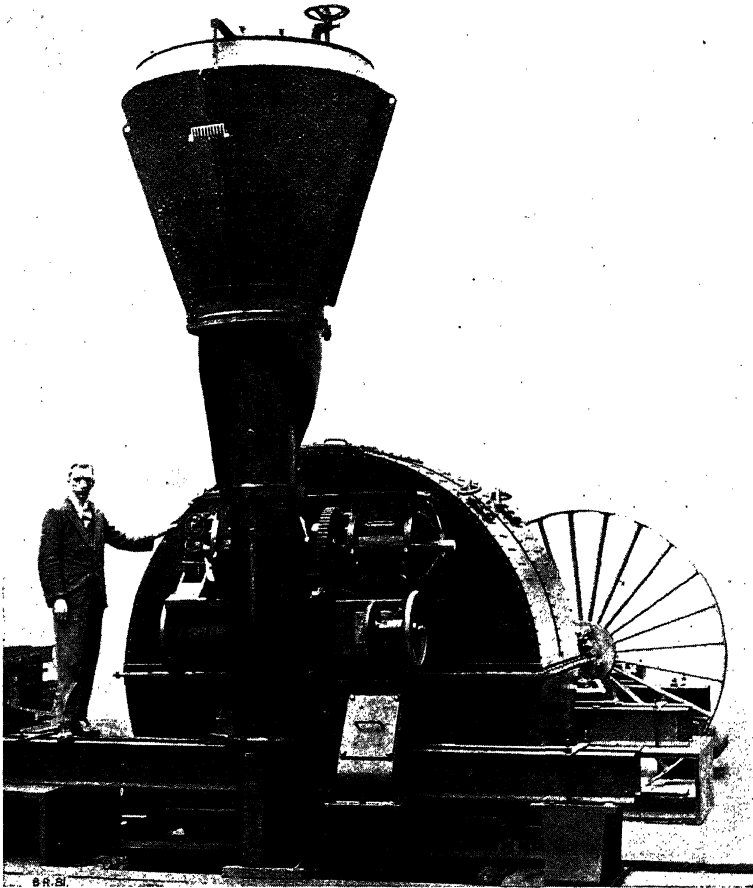


Fig. 139.—Ball-mill for $3\frac{1}{2}$ Tons per Hour, with Rema Classifier.

sectional elevation of a plant with trunnion bearings at both ends; *Fig. 138* a 15-tons per hour mill having a trunnion bearing at one end and a roller-ring at the other, and *Fig. 139* a $3\frac{1}{2}$ -tons per hour mill with a shaft passing through the centre and a sleeve bearing arranged at each end. This last plant is specially arranged so that the coal may be fed either directly to the mill or into the hot air stream.

Referring to *Fig. 137*, coal from the hopper (A) is fed into the ascension pipe (B) through a feeder (C) which must also prevent air leaking with the coal into the

system. As will be explained later, this is a most important point. Hot air is supplied to the system through the pipe (D) and passes along the horizontal part to the pipe (B); here it meets the incoming raw coal which is endeavouring to fall by gravity down the pipe (B). The velocity of the air is, however, sufficient to bring the coal to rest and start it in motion upwards. The air and coal then travel in the same direction until they reach the top of pipe (B) in the bottom of the separator (E); here there is fitted a deflector (F) against which the coal and air impinge and are caused to change direction. At the same time expansion of the air takes place in the separator and the first classification of the coal takes place. The coarse coal drops to the bottom of the separator and is fed by the duct (G) into the mill via the hollow trunnion (H). The finer coal is borne by the air to the top of the separator, where a further classification takes place in passing through the tangential opening (I) between the outer and inner portions of the separator. Inside the inner separator expansion again takes place, and the finest of the coal passes away with the air, which is now much reduced in temperature, to the fan by which the air is induced through the system. The less-fine coal drops to the bottom of the inner separator and passes out through the non-return flap valves (J) to the bottom of the outer separator and via the duct (G) to the mill for further grinding.

The raw coal, having been freed from "fines," reaches the mill and is ground by impact and attrition as in other mills of the same type. As there is no flow of air through the mill the coal is discharged in the ordinary way and delivered by the pipe (K) back into the air stream at (L). It then mixes with the raw coal which is being fed continuously into the system and is again passed through the separating system. Due to the small charge of grinding media the quantity of coal in the mill is reduced to a minimum. The efficiency of the system is dependent on keeping the coal in the mill the shortest possible time, and on separating the "fines" as soon as they are produced.

Any tramp iron or stone which is fed in with the coal is not carried up the ascension pipe owing to its greater density, but drops to the bottom of the bend (M) where it can be removed through the valve (N). The velocity of the air in the pipe (B) must be maintained at about 90 ft. per second, which is sufficient to lift coal up to $1\frac{1}{4}$ -in. cube. It is important that the system be kept air-tight, for if infiltration of air is allowed to take place, e.g. where the coal is fed in, the velocity of the air in the lower part of the ascension pipe is reduced, the coal is not lifted, the bend (M) becomes blocked with coal, and the whole system ceases to operate.

To induce the air through this system requires a suction at the fan inlet of from 12-in. to 15-in. water gauge. Although this increases the fan duty, the saving in power on the mill due to the coal being fed into it in an ideal condition for grinding more than compensates for this power expenditure.

The following power consumption per ton of coal pulverised may be obtained under average conditions for mills of from 3 to 5 tons per hour capacity: Ball-mill, 13.5 kW. hours; fan and feeder, 9.5 kW. hours; total, 23.0 kW. hours.

Crushing Mills

A number of mills come under this heading, most of them employing either a number of large balls or rollers which are made to run round inside a grinding ring against which the coal is crushed. The Griffin, Fuller-Lehigh, and Bradley mills grind in this way, and have been used in the cement industry for various purposes for many years.

The Rema ring-mill (*Figs. 140-142*), which is a form of Kent mill, employs the Rema vacuum system described in reference to the ball-mill. *Fig. 142* shows how easily the grinding unit can be removed from the casing.

Referring to *Fig. 141*, the raw coal is fed in at (A) and after passing through the separating system is fed into the mill at (B). The mill consists of three rollers (C), (D), (E), around which the grinding ring (F) runs. Roller (C) runs on a shaft, the bearings for which form part of the sides of the machine. All the power is transmitted by this roller to the grinding ring which it rotates. The ring drives the two

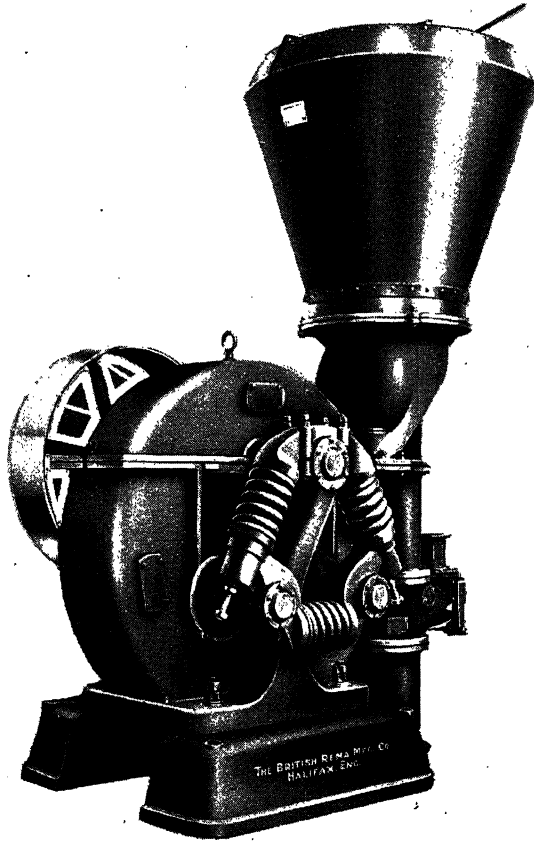


Fig. 140.—Ring-mill with Rema Classifier.

idler rollers (D) and (E). The bearings for the latter are free and outside the mill casing; the rollers are kept against the grinding ring by the triangular formation of the springs seen in *Fig. 140* which operate through the medium of the roller shafts and bearings. The coal is fed between the ring and roller (D) and is crushed between them, the other rollers, of course, doing their share of the work. The crushed coal drops off the ring into the bottom of the casing, which is connected through a pipe (G) to the air system. The crushed coal is then classified in the separator, the coarse being returned to the mill for further grinding as in the ball-mill. Owing to the short length of time the coal is in the ring-mill there is little doubt that it circulates

many more times through the system than in the case of the ball-mill. This renders the ring-mill less sensitive to moisture in the coal.

The power consumption for the mill is 8.5 kW. hours and for the fan 8.5 kW. hours, a total of 17 kW. hours per ton of coal pulverised. These figures are for hard Newcastle district coal and with the fan delivering 28 per cent. of the total air for combustion against a static resistance of $2\frac{1}{2}$ -in. water gauge. With a hot air supply at a temperature of 350 deg. F. there is no difficulty in dealing with coal containing up to 15 per cent. moisture. It is possible with the separator used on this system

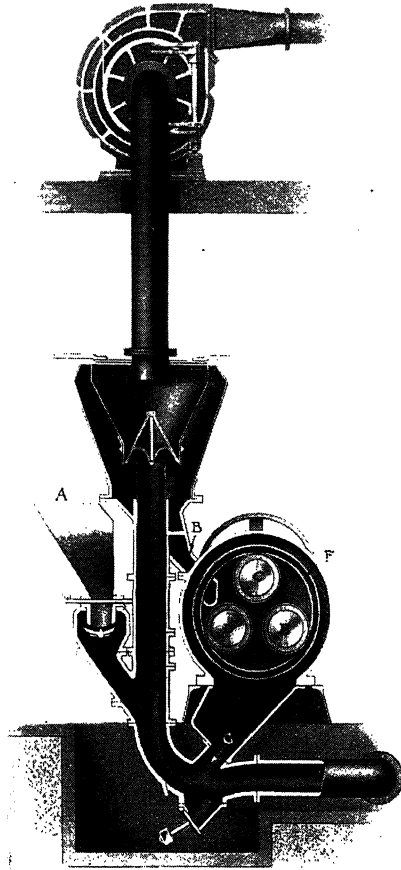


Fig. 141.—Sectional Elevation of Ring-mill.

to obtain a fine product, but the power consumptions mentioned refer to the plant when grinding to the following residues: On the 170-mesh sieve, 20 per cent.; on the 100-mesh sieve, 10 per cent.; on the 72-mesh sieve, 0.5 per cent.

The Raymond-Lopulco mill (*Figs. 143 and 144*) was developed in Germany under the name of the Loesche mill. In this case the grinding ring or pan is positively driven; the three rollers are out of contact with the ring when the mill is running light, and are only driven by the frictional contact of the coal which is ground. Some of the advantages claimed for this mill are that the whole of the lubricating system is external to the mill and that each roller can be independently adjusted

from the outside while the machine is running. Each roller is fitted through a form of hinged door so that it can be swung out for inspection or replacement. Coal enters at A (*Fig. 143*) and falls on to the grinding ring (B) which drives the rollers (C) through the layer of coal. Hot air is drawn in round the belt (D) by the fan attached to the outlet of the separator (E), which sweeps the mill at a low velocity. The coal

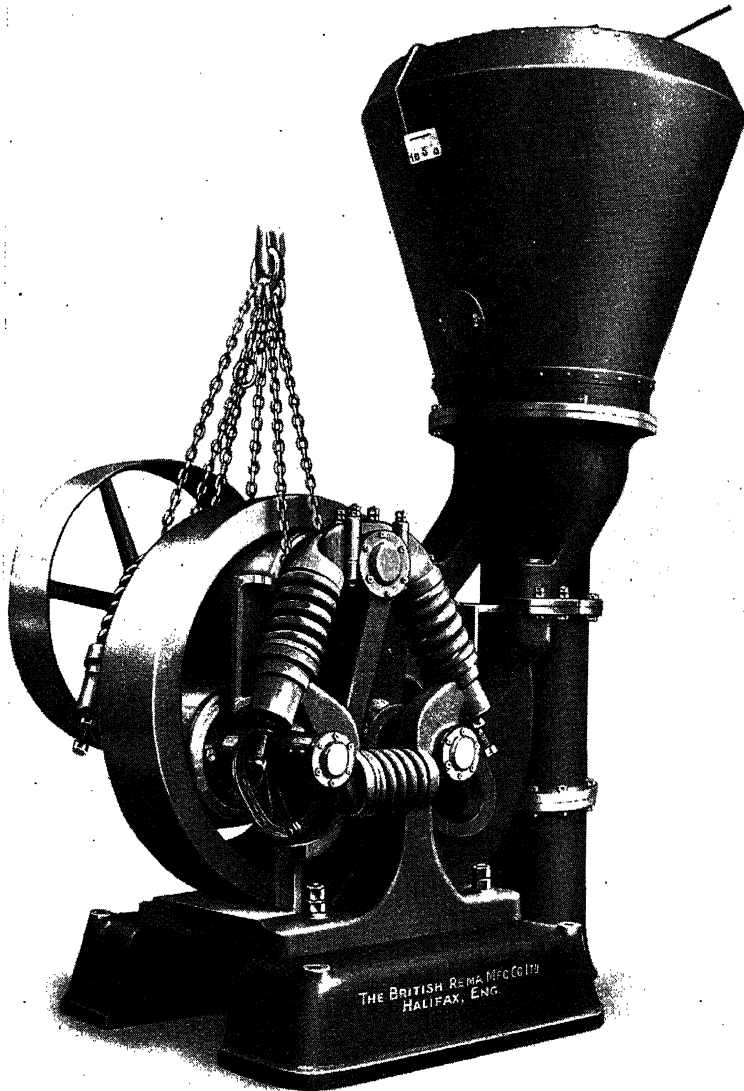


Fig. 142.—Removal of Grinding Unit from casing of Ring-mill.

which is sufficiently fine is borne away by the air, but the heavier particles fall back into the mill for further grinding. The power consumption is stated to be 10.75 kW. hours for the mill and the same for the fan, making a total of 21.5 kW. hours per ton of coal pulverised. The grinding ring runs at about 120 r.p.m., but this varies with the size of the mill.

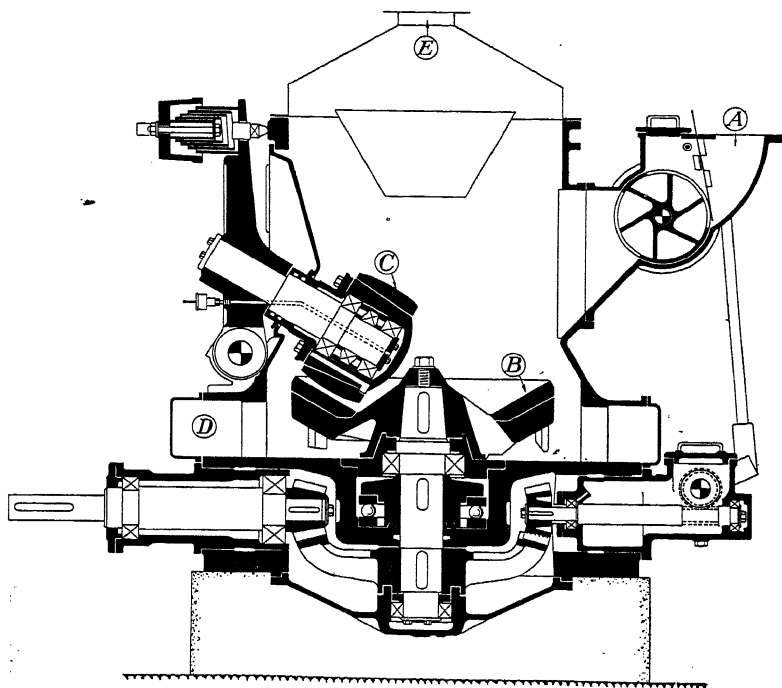


Fig. 143.—Section of Raymond-Lopulco Mill.

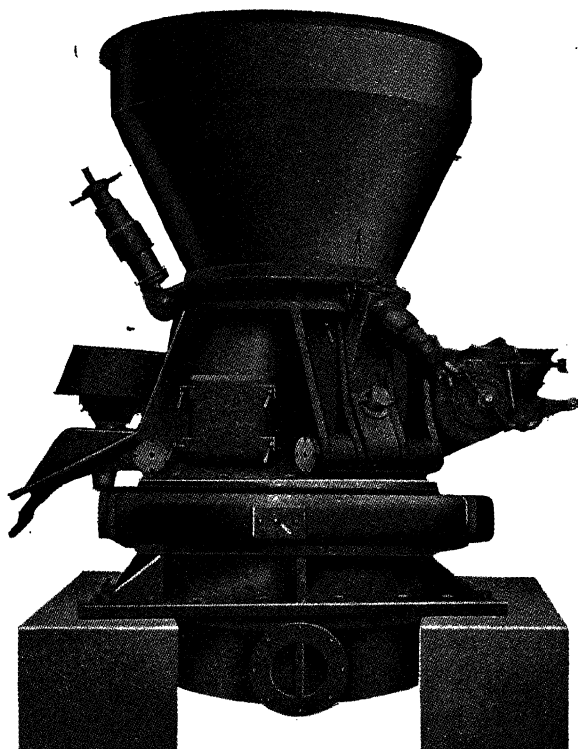


Fig. 144.—Raymond-Lopulco Mill.

CHAPTER XV

CLINKER GRINDING

THE grinding of the prepared clinker is a very important operation, for no matter how good the raw material used, how fine the raw grind, or how perfectly calcination is effected, much of the value will be lost if final grinding is not satisfactorily carried out.

Clinker from shaft or other similar kilns is usually reduced to small size by crushers of one of the types discussed earlier, but from that point onwards it is dealt with by machinery similar to that required for normal rotary kiln clinker.

Clinker leaves the rotary kiln cooler in the form of nodules, 90 per cent. of which will probably pass through a $\frac{1}{2}$ -in. ring and 25 per cent. will pass a $\frac{1}{8}$ -in. ring; 10 per cent., however, will possibly be of mass clinker, 2 in. or 3 in. overall, or even larger, and will require crushing. A high percentage of ash in the fuel is the primary cause of mass clinker formation, and this mass clinker, when it breaks away, requires crushing before it is fed into the mill.



Fig. 145.—Mill Stones in Early English Cement Works.

When rotary kiln clinker is produced from slurry with high moisture content, or slurry which is fed by sprays, the nodules are small; when clinker is produced from slurry having low moisture content the nodules are larger. But whatever the size of the nodules, good and well-burnt clinker is very hard all through, but with a still harder surface skin. It would appear at first sight that the clinker lumps might prove troublesome in grinding. This, however, is not so, provided suitable arrangements are made for crushing or breaking down. The small ball-like nodules, having a hard and relatively smooth surface, are more difficult to deal with.

The design of most grinding mills imposes a maximum on the dimensions of the nodules. This limit is reached at, say, a $\frac{3}{4}$ -in. ring, or up to a $1\frac{1}{2}$ -in. or even a 2-in. ring, according to the kind of mill, the type of feed gear, and the dimensions of the feed opening. A crusher is invariably used to reduce the oversize clinker to the desired dimensions. In any case the output of any mill can be better maintained

and the power per ton of product reduced if the feed is suitable; moreover, it is more economical to break down in crushers than in a grinding mill.

Crushers of the roll, jaw, or hammer type may be used for this duty, but roll and jaw crushers are in most general use, and these machines generally require less upkeep. To keep the cost of maintenance low, only the clinker which requires crushing should be passed through the machine. The wear of those parts of the machine that effect crushing is considerable, and they are, therefore, made removable and renewable. The metal generally used for the renewable parts is manganese steel or white iron, the latter being cast in chills. The former metal is more costly, but under some conditions will give a longer working life and prove more economical. No machining of either of these metals is possible, nor should it be necessary. When the quantity of oversize clinker is large and crushing is continuously needed, the

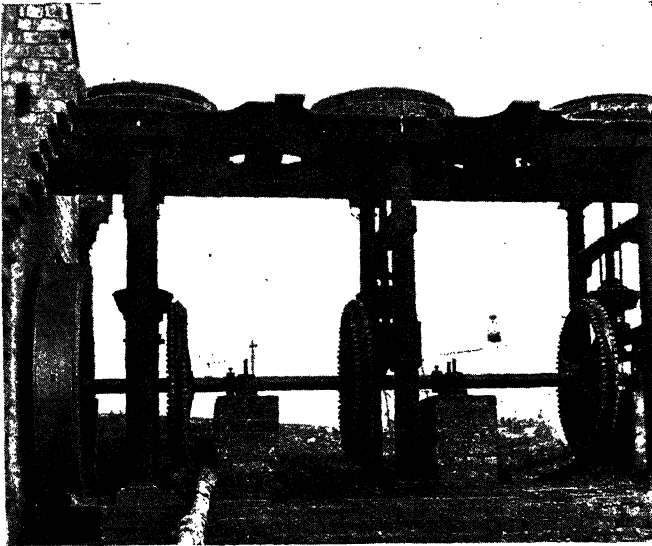


Fig. 146.—One of the Original Cement Grinding Mills installed in Australia.

power required will be, say, 1 to 2 b.h.p. per ton of clinker crushed; if the quantity is small and crushing less frequent, the power per ton will be higher.

The design of grinding mills has passed through many changes in recent years. Many mills formerly used have become obsolete and are not now being manufactured. Of those that remain, each has one or more good points; but the tendency towards the use of larger units and the need of keeping the operating cost low has brought about entirely different designs. Up to a few years ago two-mill units were very popular; they were usually paired as ball and tube, Kominor and tube, Griffin and tube, Edgerunner (various types) and tube, pulveriser and tube, etc. The first-mentioned mill in each case operated as the preliminary unit and the latter as the finishing unit. A sieving element was incorporated in the preliminary unit or between it and the finishing unit. The reduction capacity of the finishing mill invariably determined the best size of sieve opening in the preliminary mill. The ball or Kominor and tube unit was probably the most popular of all these combinations and in most general use. The Kominor mill is generally similar to the ball-mill, the only difference being in the construction and detail of the sieves.

Ball Mills

The ball-mill is a cylindrical drum mounted upon and rotated by a steel shaft. It is lined with stepped and perforated steel plates. Steel balls of from 5-in. to 2-in. diameter are used as the charge, and the material fed to the mill is crushed and partly ground by impact as the balls fall from step to step. Grading or classification in this type of mill usually takes place in three stages: (1) through the perforations in the stepped plates; (2) through an inner sieve-plate; (3) through a much finer outer sieve or sieve-plate. The oversize from each stage is returned to the mill for further reduction, but the product passing the outer sieve goes to the finishing mill. In *Figs. 147 and 148* the shaft with driving and feed naves, perforated grinding plates

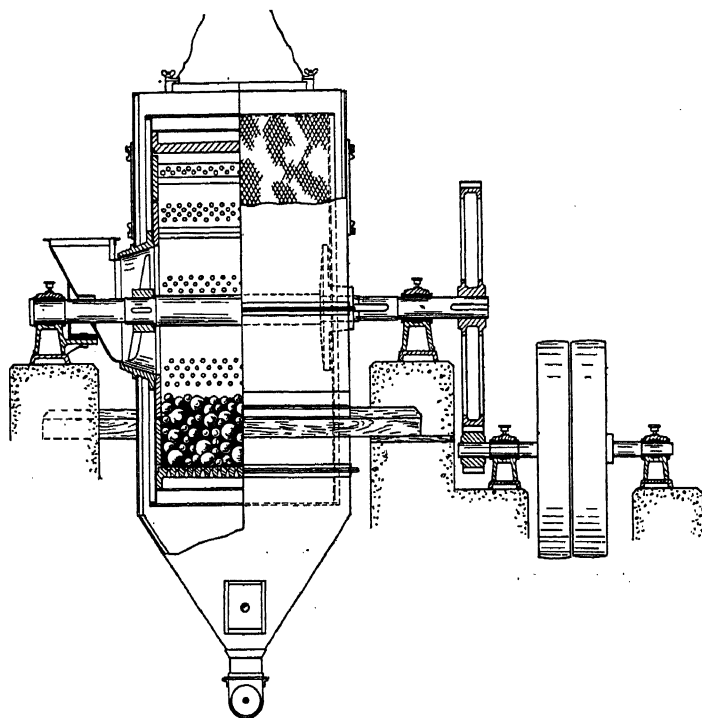


Fig. 147.—Longitudinal View of Ball-mill.

with charge, inner and outer sieves, and casing with spiral conveyor for taking the ground product away, are shown.

Figs. 149 and 150 show similar views of a Kominor mill having "fastax" sieves; the partly-ground material is passed from the mill to the screen; that which is already sufficiently ground passes through the screen in the usual way, and that which is still oversize is returned to the mill through the trunk chutes. The larger sieve area of the Kominor mill gives it a decided advantage over the older type of ball-mill. In *Fig. 151* the ball-mills are arranged at a higher level than the tube-mills and the product of the former is delivered, as feed to the latter, by means of a spiral conveyor.

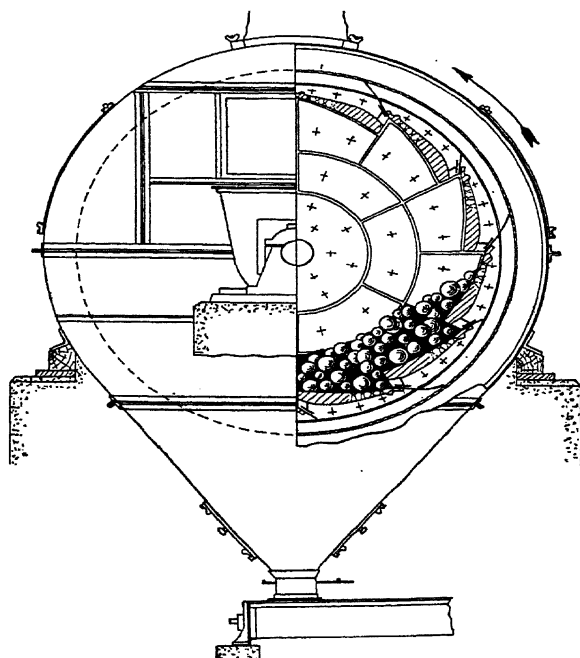


Fig. 148.—Transverse View of Ball-mill.

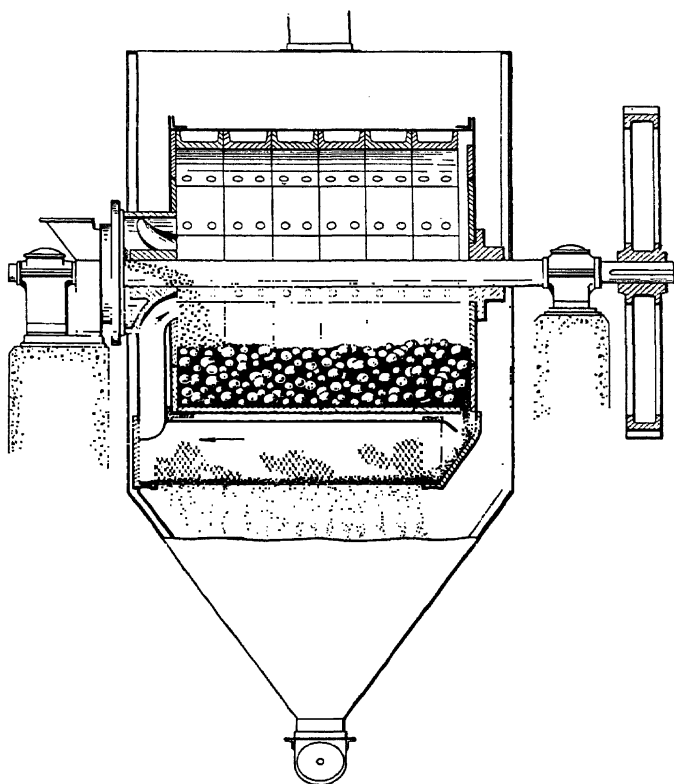


Fig. 149.—Longitudinal View of Kominor Mill.

Tube Mills

The tube-mill is employed for the cement finishing process. Grinding was originally effected by means of pebbles, but metal pellets are now used. The tube-mill, as its name implies, is a cylindrical shell usually supported on trunnion ends, lined with "sillex" or metal blocks, loaded with grinding media, and rotated. The diameter of tube-mills varies from 4 ft. to 8 ft. and the length from 20 ft. to 45 ft. The volume of charge may be from 20 per cent. to 40 per cent. of the mill volume. The grinding media are usually white iron balls from 1 in. diameter to $\frac{3}{4}$ in. diameter; a rather larger diameter may be an advantage if the feed particles are of large dimen-

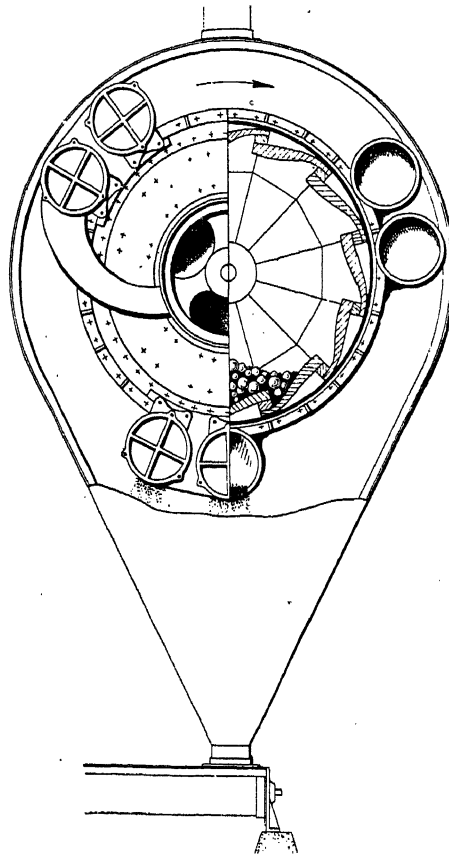


Fig. 150.—Transverse View of Kominor Mill.

sions, but if the product is to be very fine the whole of the grinding media may be rather smaller. Some millers prefer to use media of slightly different form, say, $\frac{3}{4}$ in. in diameter by $1\frac{1}{4}$ in. long or $\frac{5}{8}$ in. diameter by 1 in. long; this form of media, however, can only be used efficiently when the mill speed is low.

The speed of the mill's rotation for fine grinding should satisfy the equation

$$\text{r.p.m.} = \frac{220 \text{ to } 230}{\sqrt{d}}$$

where d is the effective diameter of the mill in inches. This speed will produce

the cascading of the grinding media indicated in *Fig. 152* for large-diameter media and stepped plates, and in *Fig. 153* for small-diameter media and plain surface lining. With mill sizes, loads, and speeds given, the b.h.p. will be 15 to 18 times the weight of the charge media in tons.

A typical classification of feed for a finishing tube-mill is as follows :

Residue on the	18-mesh sieve	20 per cent.
"	" 72 "	52 "
"	" 100 "	61 "
"	" 170 "	69 "

If the tube-mill capacity is large in relation to the amount of feed these residue figures could be increased, and vice versa.

The classification of the product will depend upon the fineness required, the suitability of the grinding media, and the amount of work absorbed in the grinding process. In England cement is usually ground to a residue of 4 per cent. to 5 per cent. on the 170-mesh sieve. The British Standard Specification allows 10 per cent. on that sieve, or, say, 17 per cent. or 18 per cent. on the 200-mesh sieve, the flour content being relatively low. If the cement is of the rapid-hardening type, with high tensile and compression characteristics, the residue may be, say, 0.4 per cent. to 1 per cent. on the 170-mesh sieve, and, say, 1 per cent. to 2 per cent. on the 200-mesh sieve, the flour content being much higher. (The B.S.S. allows a residue of 5 per cent. on the 170-mesh sieve in the case of rapid-hardening Portland cement.)

A longitudinal section through a typical finishing tube-mill is shown in *Fig. 154*. The amount of feed is determined by the preliminary mill, the grit is fed by the spiral feeder indicated, and the rotation of the mill causes the cement particles to pass through the mill. A diaphragm grid with lifters is fitted near the outlet end to keep the media in the mill and to facilitate the exit of the cement. The circular screen at the discharge is fitted to prevent any of the charge being passed out with the cement.

— Compound Mills

The compound or multiple-chamber mill (*Figs. 155-158*), introduced about 1920, has become very popular, and a large number of the new mills now installed—certainly all the largest—are of this type. In principle, this is a ball and tube mill combined; in construction it is a tube-type mill of much greater size than the early tube mills, divided into a number (three or four) of compartments, each compartment being loaded with grinding media suitable for its particular duty. The shell is 7 ft. to 8 ft. 6 in. in diameter; the length between end covers is 35 ft. to 45 ft.; the charge load (balls or equivalent) weighs 40 to 60 tons; the diameter of the media varies from $3\frac{1}{2}$ in. or 4 in. to $\frac{3}{4}$ in. or $\frac{5}{8}$ in., and the smaller may alternatively be egg-shaped, say, $\frac{5}{8}$ in. in diameter by $\frac{7}{8}$ in. long. The mill shown in *Fig. 155* is divided into three chambers; the first two chambers are lined with chrome steel stepped plates and loaded with forged steel balls, and the last chamber is lined with white iron bricks and loaded with white iron balls or pellets. A grid-plate is interposed between chambers 1 and 2, and also between chambers 2 and 3. A similar grid-plate with lifters is arranged at the outlet end. The volume of the charge in the mill shown is 20 per cent. to 28 per cent. of the mill volume. It is not unusual for the charge volume to be as high as 35 per cent. or even 40 per cent. of the mill volume if the shell is strong enough and the motor sufficiently powerful; in such cases, however, the operating speed should be slightly higher. Some millers prefer a de

charge to a shallow charge, and where power is limited or the duty of a mill is small it is sometimes preferred to reduce the effective length of the mill in order to obtain the deeper charge. There is no proof, however, that this results in higher efficiency or lower b.h.p. per ton.

Compound mills of the larger sizes are sometimes made of large diameter for a short length at the feed end; this, however, causes constructional difficulties,

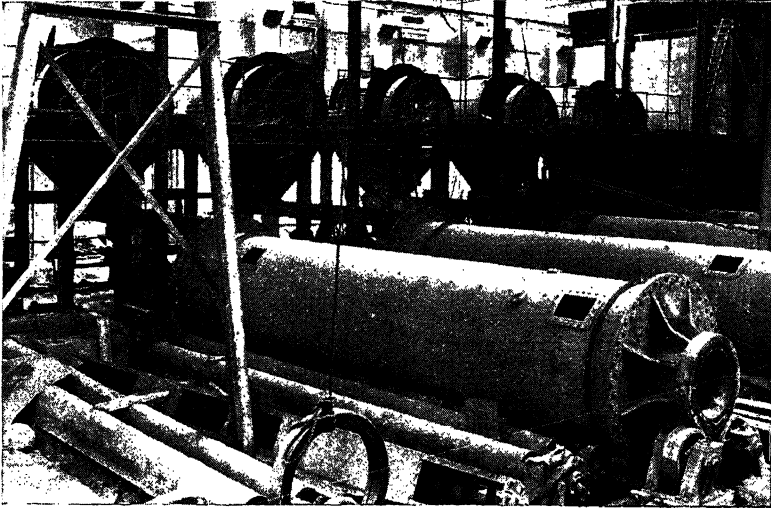


Fig. 151.—Grinding Mill, showing Ball-and-Tube Mills during Erection.

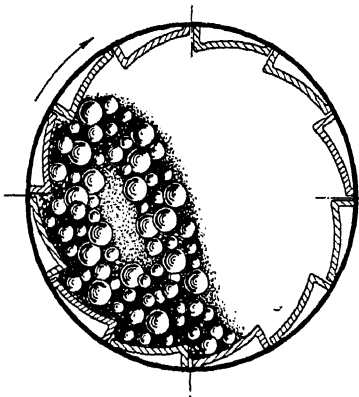


Fig. 152

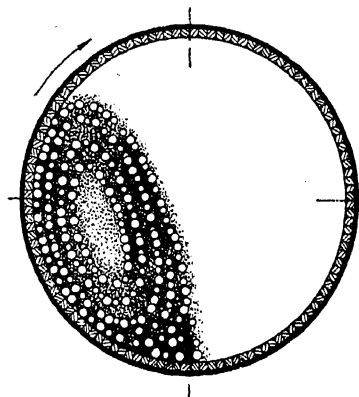


Fig. 153

Path of Charge in Cement Grinding Mills.

and there is no real evidence that the complication is warranted. A screening element is also frequently interposed between the first and second chambers; this should reduce the b.h.p. per ton necessary for grinding, but the constructional difficulties are serious and a more highly skilled operator is required. Compound mills can be manufactured in any size capable of absorbing any reasonable amount of power.

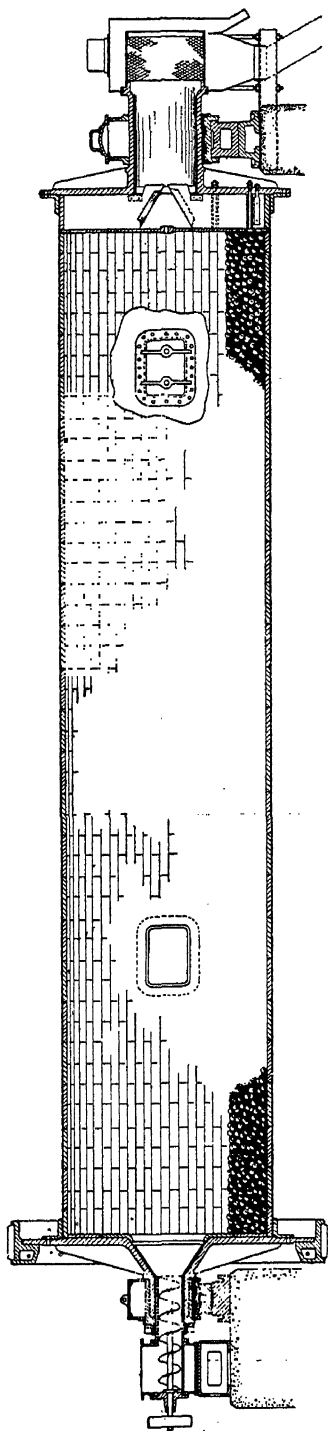


Fig. 154.—Longitudinal Section of Tube Mill.

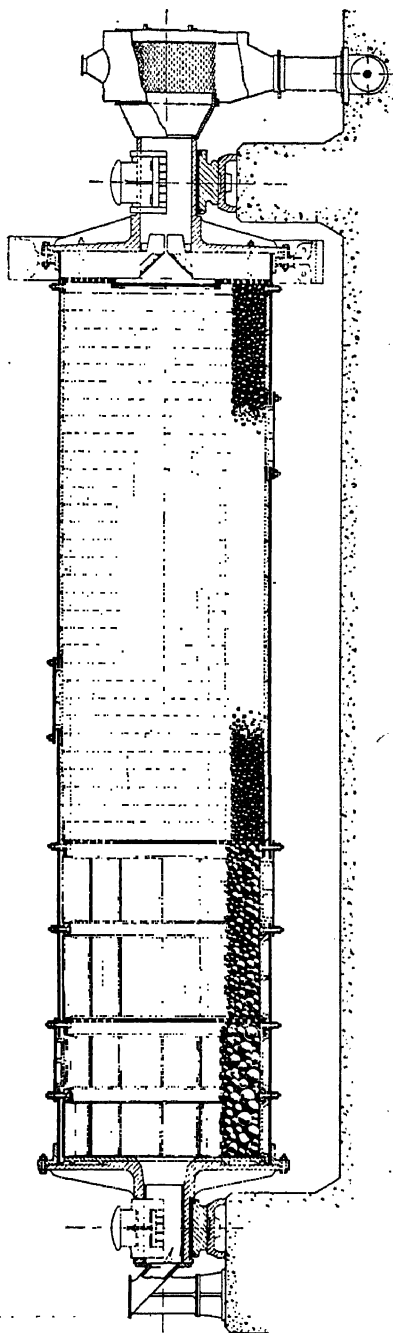


Fig. 155.—Longitudinal Section of Compound Mill.

Grinding in compound mills is effected almost exclusively by percussion. The rotation of the mill and the friction of the charge load on the mill-lining cause the balls to be raised and thrown down to the toe of the charge. This action is con-

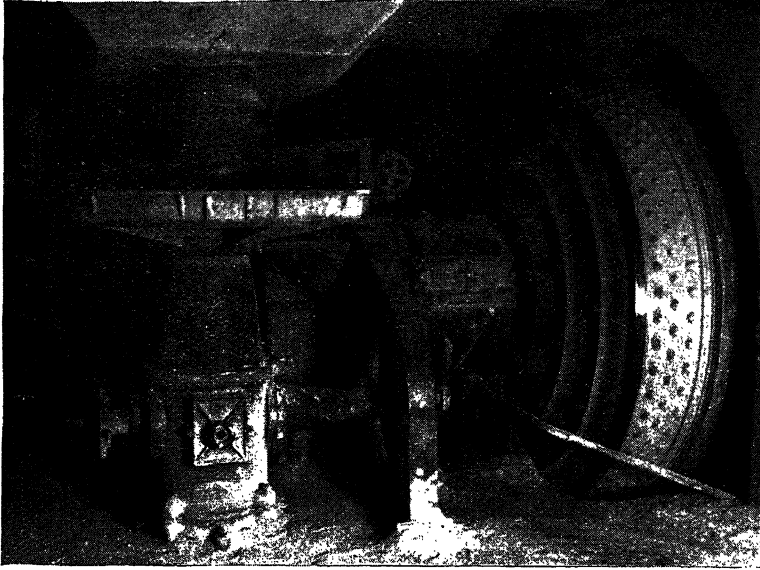


Fig. 156.—Feed End of Compound Mill with Table Feeder.



Fig. 157.—Outlet End of Compound Mill.

tinuous. It is probable that each ball strikes three blows for every two revolutions of the mill. The rules for speed, loading, and power of these mills are in general agreement with those previously given for tube-type finishing mills.



Fig. 158.—Compound Mills with Access Platform.

Open and Closed-Circuit Grinding

The grinding carried out in the mills previously described is on the open-circuit system. Closed-circuit grinding has been adopted in this country only in exceptional cases. In open-circuit grinding the material only enters the mill once. It is kept in the mill and subjected to the grinding process until the grinding, as determined by the limitations imposed by the residue, is completely effected. The amount of mill feed is thus at all times nominally equal to the amount of mill discharge. In closed-circuit grinding the material is in continuous circulation, being passed through the mill and classified continuously until it has been reduced to the desired size.

A strong claim made for closed-circuit grinding is that, owing to continuous classification, the material is passed from the mill and out of the mill circuit as soon as it has been sufficiently reduced, and is thus prevented from muffling or cushioning the material still in process of grinding. But the principal claim is that closed-circuit grinding increases the output of the mill unit by as much as 10 per cent. to 20 per cent. It should be pointed out, however, that the grading of cement produced by open-circuit grinding is such that higher strengths, both tensile and compressive, are obtained. Microscopical examination of the products obtained by the two methods reveals that with the same sieving classification the amount of fines obtained in open-circuit grinding is much larger than that obtained in closed-circuit grinding. It appears that the further reduction of the particles after the sieving classification conditions have been met results in a lower average particle dimension, and this grading of the fines with smaller particle dimensions gives the product of open-circuit grinding a cementitious value not yet obtainable in closed-circuit grinding. The characteristics of the product of percussion-type preliminary mills differ from the characteristics of the product of attrition-type preliminary mills. It is possible that the attrition unit would behave well and produce an ideal cement under closed-circuit conditions if the final classification were sufficiently under control; this completeness of control has, however, not yet proved possible.

CHAPTER XVI

DUST COLLECTION

Dust arises at three stages, namely, in connection with (1) raw materials (crushing and grinding and kiln gases), (2) coal, and (3) the finished article. Generally speaking, all dust which has to be collected at cement works is very fine, and systems applicable to other conditions, such as steam-raising plants, are very often unsuitable. The collection of the raw-material dust from the kiln gases constitutes the most difficult problem, owing to the large volume of gases involved and—with the wet process—their high moisture content.

With the older arrangements of pulverising plant, coal dust was often a serious problem. The coal dust from grinding and conveying plants can generally be dealt with by the kiln-burner fan, and so utilised in the best possible way, but gases from the dryers, which carry considerable moisture, are very difficult to clean and some form of wet washing has often proved necessary. With modern plants, however, the difficulty has largely disappeared. This is especially so in connection with "unit" pulverising plants described in a previous chapter.

Finished cement dust occurs in grinding and conveying, and later in the packing operations. In connection with dry raw mills, cement mills, and packing plants, the problem presents no very great difficulties, and is usually satisfactorily solved by fans and filtering plants.

Size of Dust Particles

The collecting methods to be employed must depend on the size of the dust particles, and it may be useful to consider this subject before proceeding to the systems available for dealing with the problem. Analysis of the results of many examinations of dust samples indicates that from 50 to 90 per cent. of the whole amount passing out of a rotary kiln with the gases will pass through a No. 240 British Standard sieve, i.e. they have a diameter of less than 0.066 mm. The No. 240 sieve is the finest which can be satisfactorily operated, and it follows that sieve analysis is of little use in connection with this problem.

Micrometer measurements which the author has made of many samples of dust show that the average diameter of the particles appears to be about 0.01 mm., that is about the size of the flour particles of finely-ground cement. It is difficult to appreciate the dimensions of particles of this minute size. It may perhaps be helpful to note that if a single layer could be arranged with all the particles touching it would require about $6\frac{1}{2}$ million particles to cover a square inch.

Apart, however, from the difficulty occasioned by the minute dimensions of the particles of dust which have to be arrested, the commercial consideration of the problem turns largely on the very large volume of gases in which they are carried. A kiln of moderate capacity providing, say, 10 tons of clinker per hour will produce gases weighing about 120,000 lb. per hour. The temperature of these will vary according to the dimensions and the efficient operation of the kiln, but will seldom be much less than 400 deg. F., at which temperature their volume will be about 2,750,000 cu. ft., i.e. about 770 cu. ft. per second. The handling of these large volumes of gases through dust-eliminating plant is a serious problem and, in connection with big kilns such as are now common, the cost of the plant is a serious item of a non-

remunerative character because the dust caught is of very low value. The provision of filters for such volumes of gas is not economic, and the moisture content would create substantial practical difficulties in operation. Apart from filters, there remain three methods, and these may be described briefly as (1) mechanical, (2) washing, and (3) electrostatic.

Mechanical Apparatus

Several purely mechanical systems have been thoroughly tested, but before considering these in detail it will be useful to consider what technical information is available as to the motion of fine dust in gases. Take first the simple case of a straight settling chamber. During its passage through this the dust is in continuous motion due to the eddying of the gases, and its settlement is therefore impeded. Nevertheless, some approximate ideas can be obtained from the consideration of what would happen if this eddying motion were absent. According to well-established laws, the rate of fall of fine particles due to gravity is inversely proportional to the

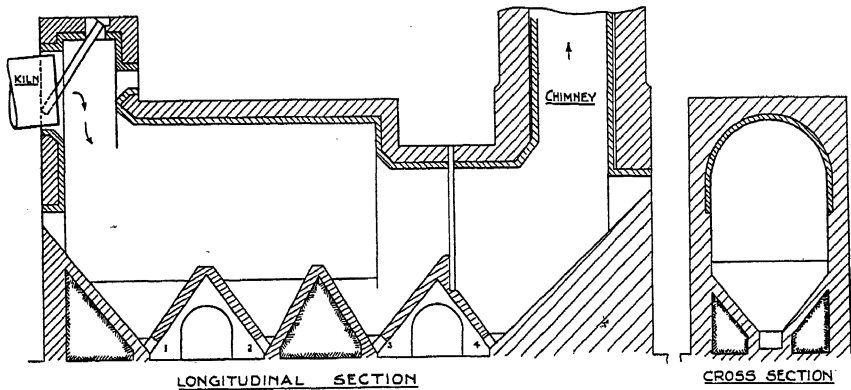


Fig. 159.—Kiln Dust Settling Chamber.

square of their linear dimensions. Spherical particles of dried slurry would fall in still air at 400 deg. F., at approximately the following velocities :

Diameter.	Speed of Fall.
0.1 mm.	25 cm. per second.
0.01 mm.	0.25 cm. per second.

Such figures could be applied to a settling chamber if eddying were eliminated, and they indicate that a particle 0.1 mm. in diameter—quite large for dust—would fall through a depth of 10 ft. in $5\frac{1}{2}$ seconds. With a horizontal gas speed of, say, 5 ft. per second such a particle would therefore fall through this height during a horizontal travel of 27 ft. 6 in. By calculation it is found that a chamber 10 ft. high and 27 ft. 6 in. long with a uniform gas velocity of 5 ft. per second should catch all particles having a diameter of 0.1 mm. or over. In practice, allowing for the fact that other shapes fall more slowly (disks being particularly slow), and for the eddying of the gases, a much larger chamber would certainly be required. To catch particles of 0.01 mm. diameter would require chambers of impracticable dimensions, and it is particles of about this size that are in question.

A typical settling chamber is shown in Fig. 159. The gas velocity in this is about 4.5 ft. per second, and it is provided with four hoppered outlets. Samples

caught from the four outlets show the following residues on the 170-mesh sieve (0.089 mm. aperture) :

Chute No. 1	75 per cent.
„ No. 2	59 „
„ No. 3	37 „
„ No. 4	10 „

These figures clearly illustrate the effect of time on the deposition of the dust. It will be noticed that the sample from No. 4 outlet is very much the finest ; of

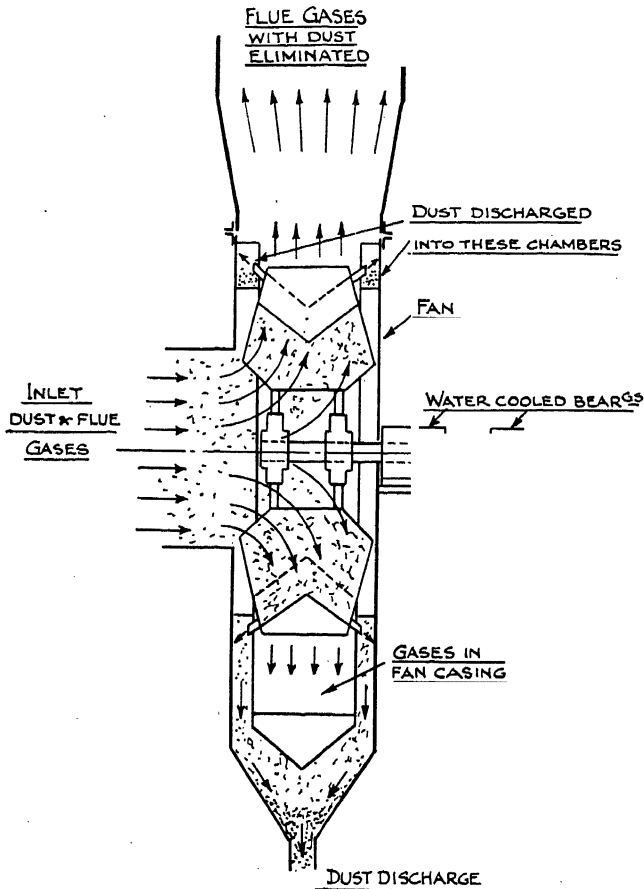


Fig. 160.—Cindervane Fan.

this about 66 per cent. passed through the 240-mesh sieve, and this fine material had an average size of about 0.027 mm. Seeing that the average size of the dust is about 0.01 mm., it follows that the larger amount of the finer material was escaping from the settling chamber. It will be seen that simple settling chambers of reasonable dimensions would hardly produce satisfactory results.

The next step in mechanical systems depends on the use of separators operated by centrifugal action, and in these the forces tending to eliminate the particles are much greater than gravity. The effect of size, however, would be similar to that

in the case of settlement by gravity, so that the difficulty of eliminating the particles still increases very rapidly with their reduction in size.

From these considerations it might be deduced that a mechanical system of settlement would eliminate all particles over a certain size and leave the rest in the gas. Although this is the tendency, yet in practice a large amount of fine material is eliminated, probably due to entanglement. The following systems may be described.

CINDERVANE FAN.—The principle of this apparatus (*Fig. 160*) is that the dust impinging on the blades is thrown sideways at oblique angles and discharged into narrow pockets at the side of the fan. Tests have been made on a fan of this character handling gases with a dust concentration of 6 gr. per cubic metre, and this was

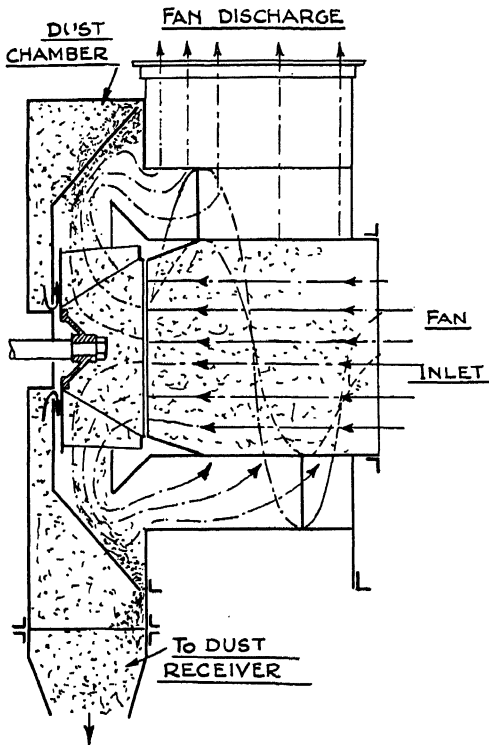


Fig. 161.—Keith Fan.

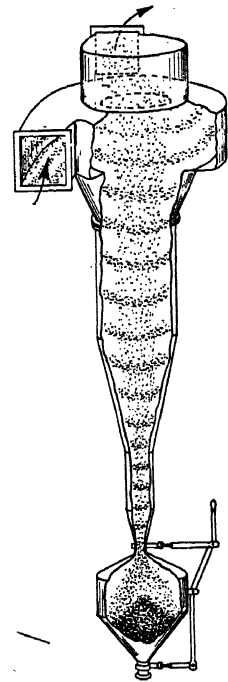


Fig. 162.—Davidson "D" Type Cyclone.

reduced to about 3.3 gr., showing that the fan was catching about 44 per cent. of the total dust. The average size of the particles caught was 0.087 mm. in diameter.

KEITH FAN.—Tests on the Keith fan (*Fig. 161*) indicate an efficiency of rather over 50 per cent. when handling gases with a dust concentration of 5 gr. per cubic metre, and it is reported as catching practically all particles measuring over 0.04 mm. but practically none less than 0.01 mm.

DAVIDSON "D" TYPE CYCLONE.—This apparatus (*Fig. 162*) appears to be an efficient form of purely mechanical apparatus. On a mixture of dust as normally produced by a kiln this separator had an efficiency of 81.7 per cent. with a concentration of 14 gr. per cubic metre and 78.7 per cent. with a concentration of 4 gr. per cubic metre. Of dust caught during these tests, 56 per cent. passed through the 240-mesh sieve and had an average size of 0.015 mm. diameter. A further test on this apparatus was made on a sample of exceptionally fine dust, and under these very

difficult conditions the efficiency was 66.7 per cent. Of the fine dust which this collector did not catch no less than 99.6 per cent. passed the 240-mesh sieve and had an average diameter of 0.0071 mm. It will be clear from this test that under suitable conditions only the finest dust escapes this apparatus. In cases where the original density is not high this class of separator may produce satisfactory results, its only disadvantage being a heavy loss of pressure through the apparatus, thus calling for a high consumption of power in the fan.

Washing Apparatus

A good deal of experience with reference to washing has been accumulated in connection with blastfurnace gases. In this case a high degree of cleanliness is necessary before the gas can be used satisfactorily, especially where it is supplied to gas engines. It is unnecessary to describe the various systems which have been developed for this purpose in detail, as such information may be found in books dealing with iron and steel works. Generally speaking, the cost of such processes in capital, water consumption, and other directions renders them uneconomic in connection with cement kilns.

Rotary-kiln gases can, however, be sufficiently cleaned to meet ordinary requirements in a plain tower fitted with sprays as illustrated in *Fig. 163*. The

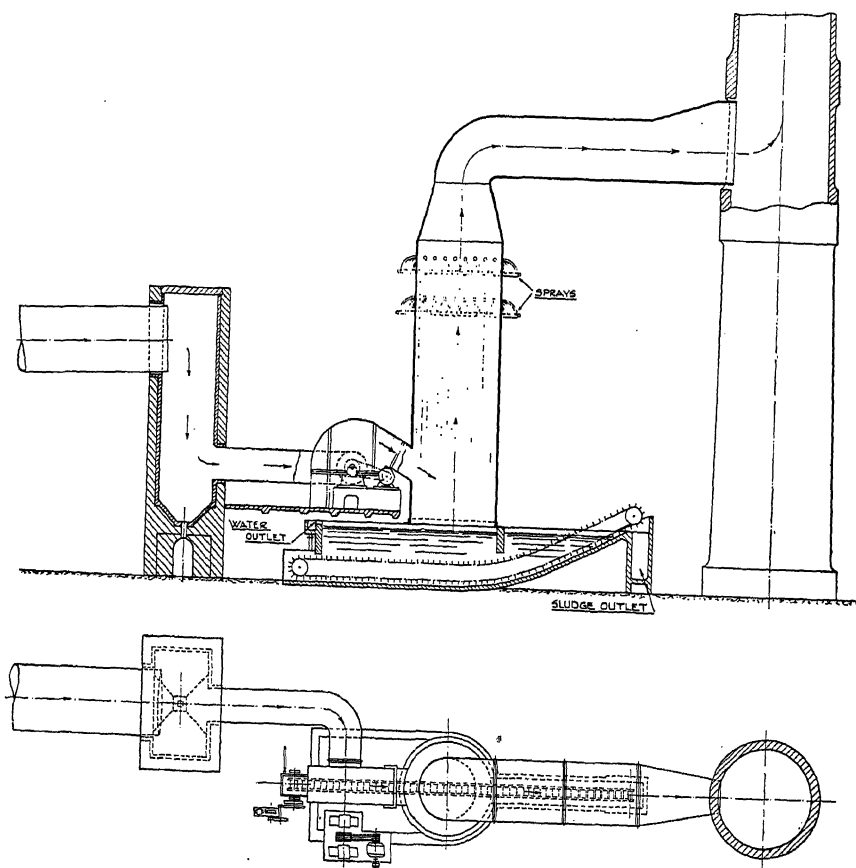


Fig. 163.—Water Spray Tower.

omission of any filling materials such as coke, wood grids, etc., such as are often used in connection with cleaning blastfurnace gas, simplifies the apparatus and considerably reduces the loss of head through the tower and therefore the power expended on fans, which would otherwise become excessive. It will be noticed that the gases pass upwards through a series of sprays in which the water is reduced to a state of such fine division that every particle of dust is wetted and thus falls down against the flow of gas.

Several difficulties arise in connection with this system, of which the first is the disposal of the sludge produced and the water. Fortunately the particles settle rapidly, and it will be noted that the tower is fitted with a tank at the base and that the water flows out at one end over a weir. During the passage of the water towards the weir the dust settles to the bottom and the sludge is extracted by a series of chain-driven scrapers which discharge over another weir at the opposite end. From here it may be pumped directly to the kiln or into further settling chambers if necessary. The overflow water, which should contain only a very small proportion of dust—and that the finest—must be disposed of according to local conditions. With many dusts there is a tendency to build up on any projection in the washing towers, including even the spray supports, thus necessitating periodical stoppages for cleaning. A further difficulty is the fact that the spray absorbs acid from the gases, and some of this is carried out as mist to the chimney. This mist can be partially removed by eliminators, as in air-conditioning plants, but even so the gases must necessarily remain saturated with acid moisture and it is necessary that the flues leading from the washing tower and the chimney should be provided with acid-proof linings.

Electrostatic Apparatus

Electrical precipitation plants may be broadly divided into two classes, those having horizontal flow between plates or wire screens, or both, and those having vertical flow upwards through tubes. In either case the dust particles are propelled by an electrostatic discharge at a pressure of from 40,000 to 60,000 volts emanating from discharge electrodes on to collecting electrodes, the latter being earthed.

It will be noticed from *Fig. 164* that the discharge electrodes consist of vertical wires hanging from insulated supports and kept taut by weights. The collecting electrodes consist of steel plates, but in some cases a screen of wires or rods is used for this purpose. In either case rapping gear—consisting of light hammers cam-operated by electric motors—is used to dislodge the dust from the electrodes periodically. Where very high efficiencies are required it may be necessary to cut off the flow of gas while the rapping is taking place, and this necessitates constructing the plant in sections with a separate control damper to each section. Such an arrangement, however, is only required in special cases, as the rapping occupies only a very small proportion of the total time and, further, only a small proportion of the dust falling from the plates is caught by the gas. The dust is discharged into hoppers below the electrodes, from which it can be removed either by conveyors or in trucks according to circumstances.

A variation of this type is the “graded resistance” precipitator, in which the collecting electrodes consist of concrete slabs about $2\frac{1}{2}$ in. thick reinforced with wire mesh for strength and also for earthing. With this type rapping is usually not required, but it has the disadvantage that the cost of upkeep of the slabs is high, very great care being necessary in their manufacture and fixing.

The upward-flow or tube type of precipitator (*Fig. 165*) was originally developed for removing mist from gases in connection with certain chemical processes, and it is now coming into use for dust removal. It will be noticed that the use of the whole area is secured for the upward flow of the gases by constructing the tubes in hexagonal form so that the group is of honeycomb form. The discharge gap from the central wire varies, of course, between the flat surface and the angles, but in practice this

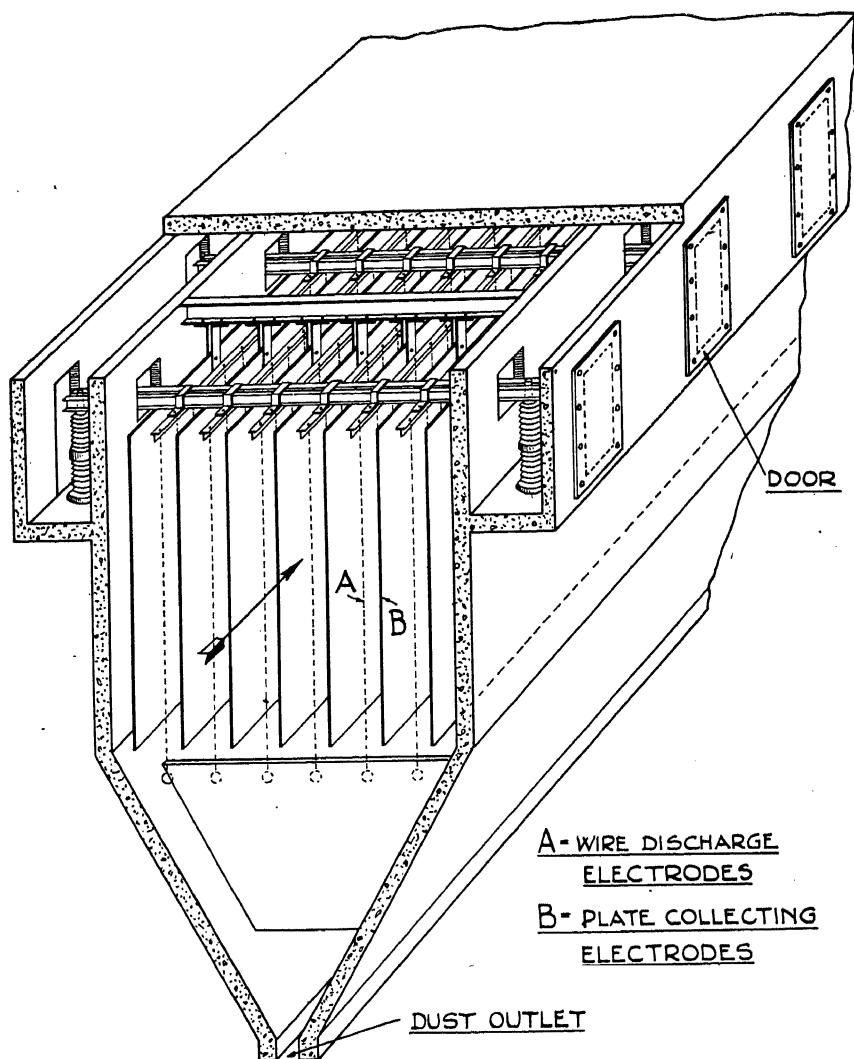


Fig. 164.—Electrical Precipitation Plant with Horizontal Flow.

is immaterial and the difference is, in fact, no greater than occurs in the plate type.

In all types of electrostatic plant the efficiency of collection depends primarily on the velocity of the gas through the plant. In general it may be taken that a velocity of about 5 ft. per second will produce an efficiency of about 95 per cent., provided the length of travel past the electrodes is adequate. Each case must,

however, be treated on its merits as various factors affect the result, such as temperature and moisture content. Within limits the presence of moisture is advantageous. The supply of high-tension electricity for the plant is generally provided

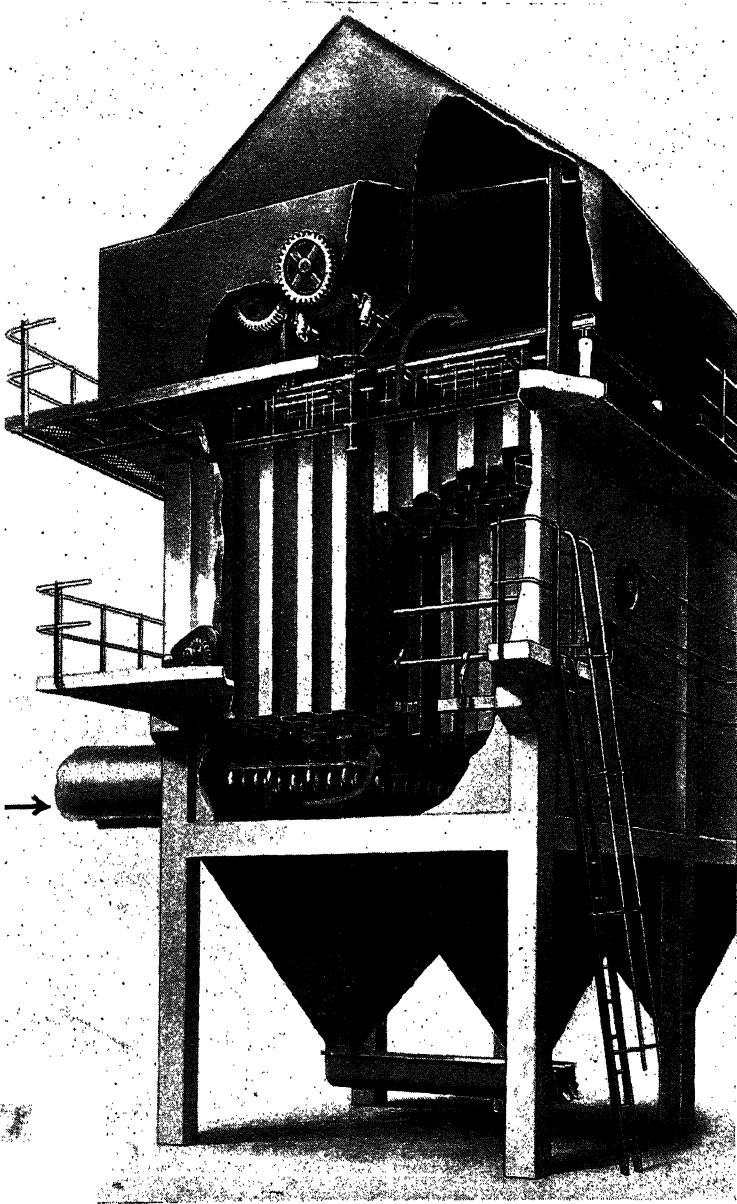


Fig. 165.—Electrical Precipitation Plant with Vertical Flow.

through step-up transformers and air-gap rectifiers driven by synchronous motors. An alternative consists of high-tension direct-current generators in series similar to those used in connection with wireless transmission.

CHAPTER XVII

POWER FOR CEMENT WORKS

THE use of electric power is almost universal in modern cement works on account of the high efficiency of generation by high-speed turbine plant, flexibility, security from service interruptions, facilities for extensions, efficiency of transmission, and the ease with which the consumption of power for various operations may be measured and recorded. There is the further advantage that the continuous operation called for from 75 per cent. of the manufacturing units enables a high load factor (say, 70 to 75 per cent.) to be easily obtained. On these grounds electric power is found to justify its adoption in almost every case.

The power required by a cement works will be controlled to a greater or lesser degree by a number of factors; three of these are

- (a) whether the manufacturing process is wet or dry,
- (b) the class of raw materials used, and
- (c) the grade of cement manufactured.

For a modern works using soft raw material with an output of 1,000 tons and upwards per week an average power consumption is 80 units per ton, giving a demand of about 0.65 kW. per ton per week on 75 per cent. load factor.

Generated or Purchased Power

On account of the high load factor, the question whether to generate or purchase the power required for a cement factory requires more serious consideration than for most industrial undertakings, but it can be taken generally that when the load is less than 1,000 kW. it will be more expedient and economical to purchase, except where special local conditions favour generation or a bulk supply is not available. For loads above 1,000 kW. the installation of power plant may be justified if a cheap supply is not available, owing to the high load factor, with consequent low capital and unit costs.

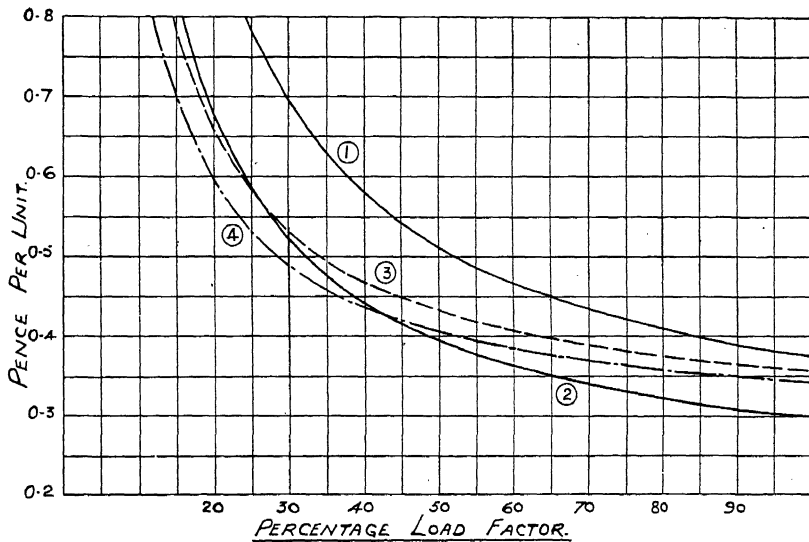
A description of the power station of a modern cement works is given at the end of this chapter. Broadly speaking, the capital cost per kW. of installed plant may be from £15 to £20, and generating costs should not exceed 0.2 pence per unit, or, allowing for reasonable depreciation and capital charges, a total cost of 0.35 pence per unit. Such figures may be taken as typical for a power plant for a large cement factory at the present time.

The bulk supply terms on which power is likely to be purchasable illustrated in *Fig. 166* are useful for reference when considering this question, and it is of interest to note that a charge comparable with the total cost of 0.35 pence per unit for generation mentioned above is only given by the terms under Curve 2.

Agreements covering purchased power require very careful preparation. Such points as kW. or kVA. charge, minimum annual payment, penalties for failure of supply, periodic revision of terms, and maximum demand call for particular attention, being often quite as important as the unit charge. The importance of the load factor (annual) on the price per unit as shown by the curves in *Fig. 166* should be particularly noted, and generally this can be maintained at 75 to 80 per cent. by

careful management, provided the output from the factory is continuous throughout the year.

In dealing with the technical aspects of the application of electric power, the following features are peculiar to or of particular interest to the industry. The system of the supply is governed to a great extent by the nature and situation of drives to be dealt with. Since the drives on cement works call for both large and small motor units (generally at a constant speed and torque, and installed sometimes over a considerable area), three-phase, fifty-cycle, alternating current as standardised in the English "grid" system is suitable for almost all the applications. Where the power to be dealt with is 1,000-kW. and upwards, 3,000-volts is an economical pressure for main transmission and direct use on motors down to 75 h.p. where the speed is low, whilst for smaller motors transforming down to a secondary pressure



No of CURVE.	FIXED CHARGE K.W. PER ANNUM.	RUNNING COST PER UNIT VARYING WITH COST OF COAL.
(1)	£ 5 · 0 · 0	0·237 PENCE.
(2)	£ 3 · 10 · 0	0·202 PENCE.
(3)	£ 2 · 15 · 0	0·28 PENCE.
(4)	£ 2 · 6 · 6	0·2775 PENCE.

Fig. 166.—Cost of Purchased Electric Power.

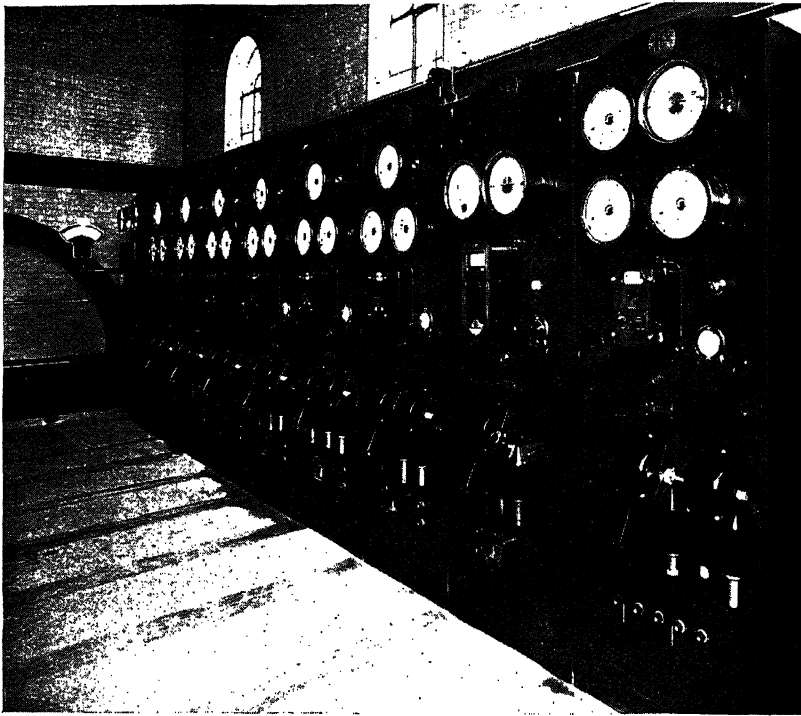
of 550/500 volts is more convenient. Preference is given to 550/500 volts over the more usual 440/400 volts, since on works where large amounts of power are involved considerable saving will be effected in copper for switchgear, cables, and control gear. The neutral point of the 3,000-volt system will be earthed, but advantages accrue from insulating the neutral point of the 550/500-volt side, and no serious objection can be raised to this. Lighting is often carried out at 230 volts, 4-wire, but 110 volts, 3-wire may be preferable for this duty for the reasons given later.

Power Distribution

The distribution of the power, with the switchgear involved, is controlled by general principles dealt with in many technical publications on this subject, but the following apply particularly to a cement works,

On large factories, with outputs of 5,000 to 10,000 tons of cement a week, and when loads between 2,500 kW. and 6,000 kW. have to be dealt with, continuity of supply to the various sections of the works will have an important bearing on output. The extent to which extra capital is to be expended on duplication of feeders with switchgear to ensure regular running may be a matter for compromise, but generally it may be justified. The additional cost involved is small in relation to the total cost of the works, and duplication facilitates the periodic inspection and testing of switchgear which is essential.

Measuring the power taken by different sections of a works, the extent to which this is required, and how it is attained, will also affect the arrangement of



**Fig. 167.—Nine Panel, 3,000-Volts, Truck Type Switchboard in Main Sub-station
(Switches : 100,000-kVA. Rupturing Capacity).**

feeders and distributors, a number of radial feeders often being necessary where otherwise a less expensive ring main would be suitable.

For switchgear controlling the primary 3,000-volt feeders, transformers, and large motors, many types are available, but for the duty in view (where the chief considerations are moderate rupturing and current-carrying capacity, maintenance, flexibility, standardisation, metering, and price), the commercially designated "truck cubicle" gear will probably be most suitable. Ironclad compound-filled gear has now been developed for industrial use, and sometimes finds a duty in the main sub-stations on large cement works. A typical switchboard is shown in *Fig. 167*.

For switching secondary or 500-volt circuits, ironclad oil-immersed draw-out unit gear may be used, and in selecting any given type the points referred to under

the 3,000-volt switchgear also require consideration, although, perhaps, not to the same degree. A suitable type is illustrated in *Fig. 168*.

Failure of switchgear from rupturing, in addition to being a source of danger to life, invariably results in cessation of supply and manufacture, which may be prolonged. That it has to be considered in relation to the 3,000-volt switchgear and circuits is fairly well recognised, but it is seldom appreciated to what extent it should be considered on the 500-volt circuits, where comparatively large powers have to be dealt with in a limited area (as often occurs on a cement works). The non-observance of this has, in some instances, meant damage to gear and loss of output owing to the failure of starters on small motors.

In the case of low-tension distribution switchgear, as distinct from motor-control gear, the rupturing capacity required from a switch under short-circuit conditions can nearly always be brought down to about 20,000 kVA. by sectionalising feeders and transformer units, and switchgear for this duty can be purchased at a reasonable price. It is not often realised, however, that in many instances on large

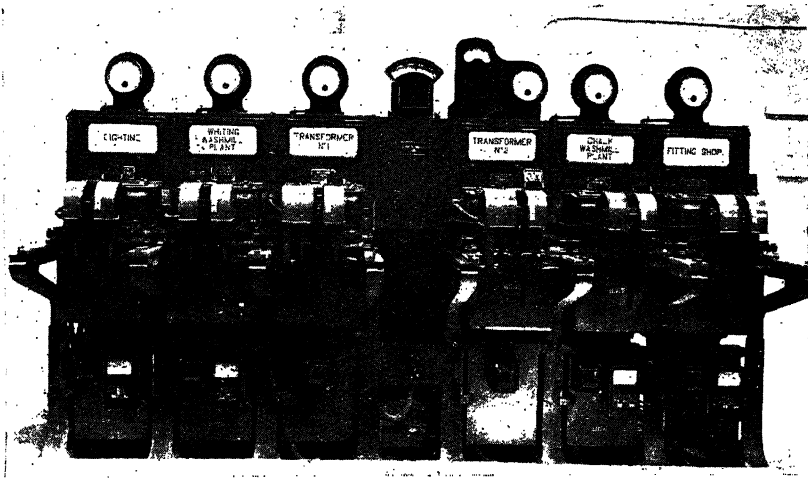


Fig. 168.—500-Volt Ironclad Switchboard in Local Sub-station.

installations the switches even on unit control gear when fitted with overload releases should have a rated rupturing capacity of 15,000 to 20,000 kVA. safely to clear short-circuit faults in the motor circuits. Control gear designed for this duty can only be obtained at prohibitive prices; fuses, however, can be obtained rated from 1,000 to 5 amperes, with a rupturing capacity of 25,000 kVA., built up into distribution boards of any number of ways desired, and they enable this difficulty to be effectively overcome at an economical cost. Such a distribution board is illustrated in *Fig. 169*.

The sectionalising and protection of each separate motor circuit by these fuses permits the rupturing capacity of the starter to be disregarded, for their current/time characteristic is such that the fuse will clear a short circuit on the motor circuit before the starter, with the inherent time lag of its protective tripping mechanism, attempts to deal with the fault.

For switch and control gear dustproof enclosures should be specified, and for the reliable operation of automatic switches total enclosure of all tripping mechanism in the switch tanks, or dustproof escutcheons, is desirable.

With ironclad switch and control gear, to ensure everything being sound mechanically and safe electrically, a totally metal-clad installation may be obtained by the use of paper-armoured cables on high-tension and low-tension feeders and distributors, and paper or rubber-armoured cables or rubber cables in conduit between motors and starters. The efficient through-bonding of all such cables and their connection to selected earth-plates on the system automatically earths all gears and motors, and also the installation as a whole.

A special cabling problem sometimes presents itself in rotary kiln houses where cables at some points have to be installed in an ambient air temperature of 150 deg. F.

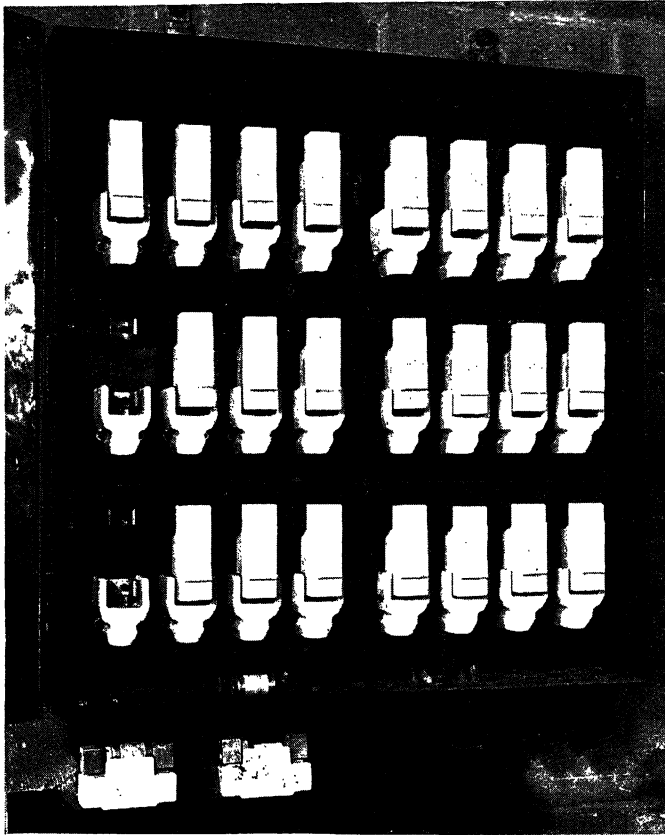


Fig. 169.—Eight-way, 500-Volts, Triple-Pole Distribution Board, Fitted with High Rupturing Capacity (25,000 kVA.) Fuses.

or higher. At these temperatures, v.i.r. and paper-covered cables will slowly disintegrate, and although cambric and asbestos-insulated cables are put forward as suitable for these temperatures they have not been found satisfactory, and if paper-covered cables are used it may be advisable to divert the runs (even at the expense of considerably increasing the amount of cable required) so that the temperature does not exceed 120 deg. F.

Step-down transformers may be considered an integral part of the electrical distribution system. These will be 3-phase units varying in size from 1,000 kVA. to 100 kVA. and built to comply with the British Standard Specification. Standardi-

sation of the size of transformers will be aimed at, and this, on large factories, is facilitated by the advisability of sectionalising the units. The load the transformers have to deal with is chiefly a balanced motor load, and although star/star windings can be used, delta/star windings suitable for dealing with some unbalanced load are preferable.

The units will be oil-cooled, and it will generally be found advisable to specify the out-door type; the slight extra cost results in the cost of sub-stations being materially reduced and permits of an arrangement as illustrated in *Fig. 170* where the space for the sub-station was restricted.

The lighting transformers will be of the same design and type as the power transformers, and when 110-volt 3-wire distribution is employed they will be of about 10 kVA. capacity, two or more being connected in parallel as the load demands.



Fig. 170.—Local Sub-station with Outdoor-Type Transformers.

A typical arrangement of the sub-stations with switchgear and feeders on a works with an output of 8,000 tons a week, taking a bulk supply of 4,500 kW., is shown in *Fig. 171*, and with the references given illustrates the foregoing remarks dealing with distribution, switchgear, and control gear.

Types of Motors

When considering the type of motor and control gear to be installed the three principal features to be kept in view are reliability, efficiency, and initial cost, afterwards providing for such special conditions as overloads for prolonged periods, heavy starting conditions, operation in dust-laden atmospheres often at high ambient temperatures, control by unskilled labour, and small opportunities for maintenance owing to long running hours. It can safely be said that the duty called for from this class of plant is as exacting on cement factories as in any other industry. Motors following standard design are suitable if the special conditions mentioned are considered.

The motors may be sub-divided into two classes: the main units varying in power from 1,000 h.p. to 100 h.p., and the auxiliaries from 75 h.p. to 1 h.p. or less, probably 90 per cent. of these being about 20 h.p. For both classes continuous rating is usually required, whilst for normal conditions full-load starting torque is generally adequate. Twice full-load starting torque is sometimes required for abnormal conditions, and since this can be obtained from an asynchronous induction motor it should be provided for on both the motor and control gear, except on large drives, such as ball-and-tube mills, where $1\frac{1}{2}$ times full-load starting torque will meet every requirement, and catering for twice full-load torque increases the cost of both motor and control gear, especially the latter, beyond an economical figure.

Large motors driving tube mills, etc., are usually high-tension machines of the slip-ring or the synchronous type. For starting or controlling these units separate stator switches with hand-operated liquid rotor starters are suitable. The remarks made earlier when dealing with 3,000-volt switchgear also generally apply to the

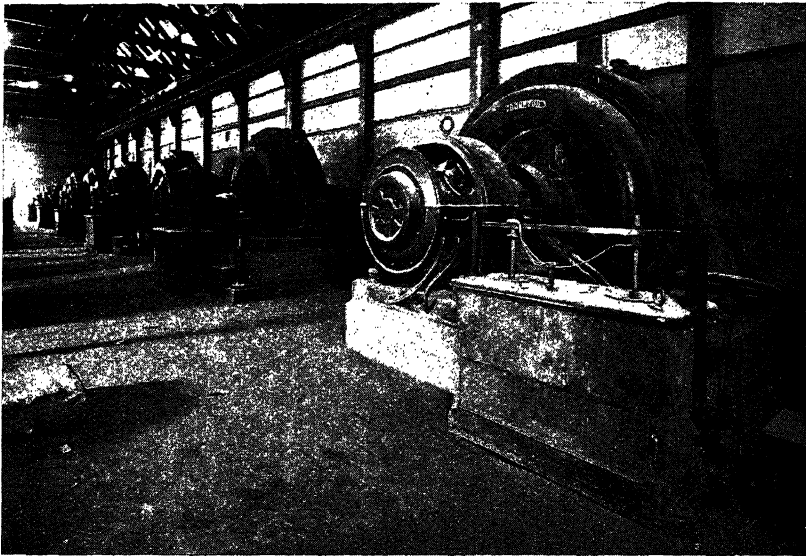


Fig. 172.—Six Auto-synchronous Motors, 750 B.H.P., 3,000-Volts, 158 R.P.M., Unity Power Factor, Driving Tube-mills.

stator switches. Liquid rotor starters of good design are adopted since they are simple in operation, low in first cost and maintenance, permit of gradual acceleration, and appreciable intermittent speed control is obtained for repairing, inspecting, cleaning out mills, etc. This speed control calls for a higher rating than the normal starting duty required, but specifying two consecutive starts every four hours against twice full-load torque with a starting period of one minute will meet all contingencies.

Large synchronous motors are widely installed for driving tube mills. Their use can be justified when the power is 300 h.p. or over on account of their high efficiency and power factor correction properties, irrespective of whether high or low-speed machines are required. Pure synchronous machines of special construction and known as "super-synchronous motors" are used in the United States, but they are not of such simple design and robust construction as the highly developed auto-synchronous induction machines installed in England.

Three tube-mill drives are shown in *Figs. 172-174*. The two latter are examples

of central drives ; the high-speed motors drive the mills through double or triple-reduction helical speed-reducers, giving a speed of 28 r.p.m. *Fig. 172* illustrates a slow-speed motor running at 158 r.p.m. and driving the mill through a countershaft

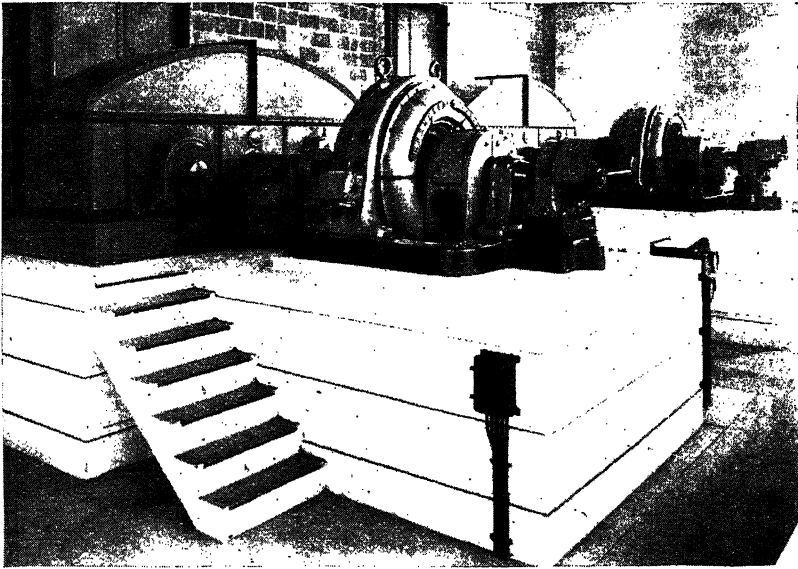


Fig. 173.—Two 650-B.H.P. Auto-synchronous Motors, 3,000-Volts, 750 R.P.M. 0.85 Lead P.F., Driving Tube Mills through Double Reduction Gears (750/28 R.P.M.).

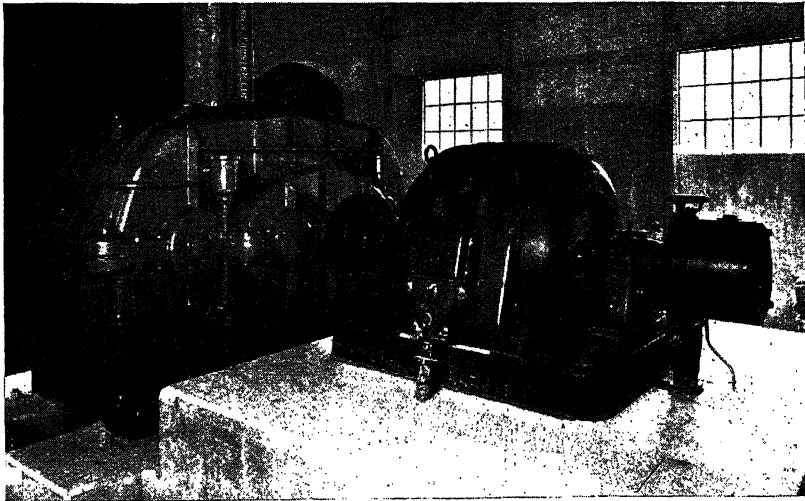


Fig. 174.—750-B.H.P., 300-Volts, 750 R.P.M., Slip-Ring Motor, Driving Tube Mill through Triple Reduction 645/25 R.P.M. Gear.

and a single-spur reduction of 6.5 to 1 ; the large pinion is mounted on the girth of the tube mill. The slow-speed drive is as commercially efficient as the central drive, and many engineers appear to prefer to eliminate high-speed motors with

gears for this class of drive. The housing of these large motor units with their control gear apart from the mills is desirable, and where they are grouped together it is advisable to ventilate the houses with washed air under pressure in the vicinity of dry grinding mills and packing plants.

For almost all auxiliary drives a final slow speed is called for, which was formerly dealt with by group drives with medium-speed motors ; the necessary speed reduction is obtained through belts or rope drives on to countershafts, with a final gear reduction on the driven unit. Owing to the adverse conditions prevailing for belts and ropes, resulting in high maintenance and renewal costs, preference was later given to individual drives with slow-speed motors and intermediate spur or worm gears. To-day, with improved high-speed gears, the tendency is to adopt individual drives with high-speed motors and large ratio double or single reduction machine-cut or worm gears, the gears being either separate units directly coupled to the motors or built into the motors to form one unit. High-speed motors and gears for the powers

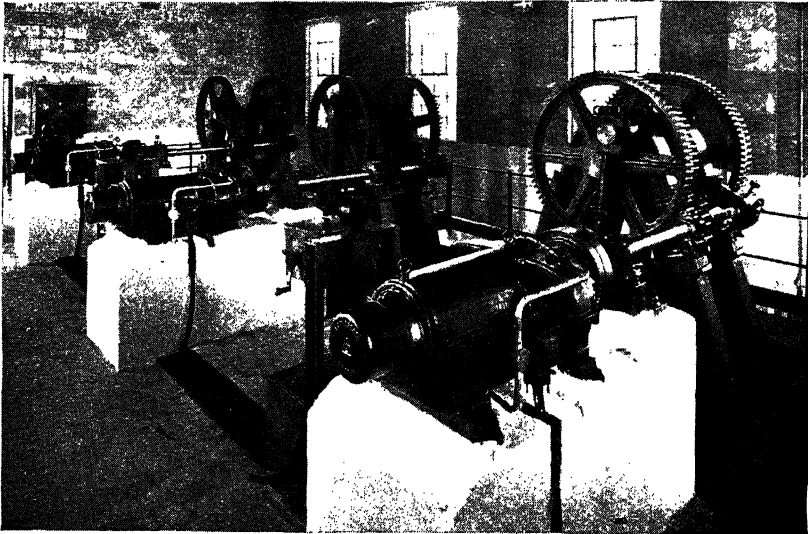


Fig. 175.—50-H.P. Motor Reduction Gear Units, 1440/75 R.P.M., Driving Slurry Pumps.

in question may entail slightly higher first cost, but higher efficiency, lower maintenance, improved electrical performance, and reduced housing space required may make them the more economical proposition.

On the Continent of Europe a large range of efficient and reliable enclosed and ventilated motors with built-in gears varying from 500 h.p. to 2 h.p., with usual motor speeds of 1,500 r.p.m. and final shaft speeds down to 20 r.p.m., has been developed and widely installed. Apart from space-saving and assured alignment of a single independently-erected electro-mechanical unit with shock-absorbing features, by incorporating double helical gearing, overall efficiencies of 93 per cent. and power factors of 0.92 are obtained, and a cement works installation totalling 2,000 h.p. of these units is in existence where an overall power factor of 0.9 is obtained on the system without resort to any power factor corrective measures. Two types of these units are shown in *Figs. 175 and 176*.

For smaller, or auxiliary, motors standard end-shield machines of the enclosed-

ventilated type may be adopted, preference being given to a design in which all ventilating openings are vertical to ensure that no falling cement or foreign matter will enter the casing. Ventilating and cooling of the windings should be effected by

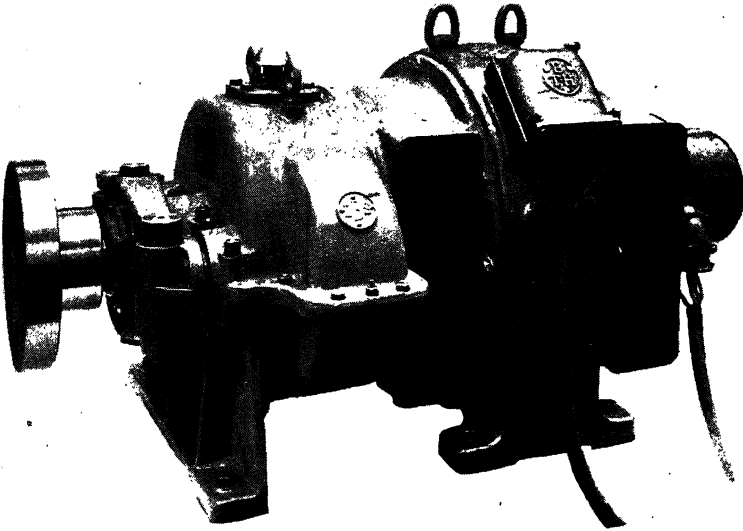


Fig. 176.—60-H.P. Motor Reduction Gear Unit.

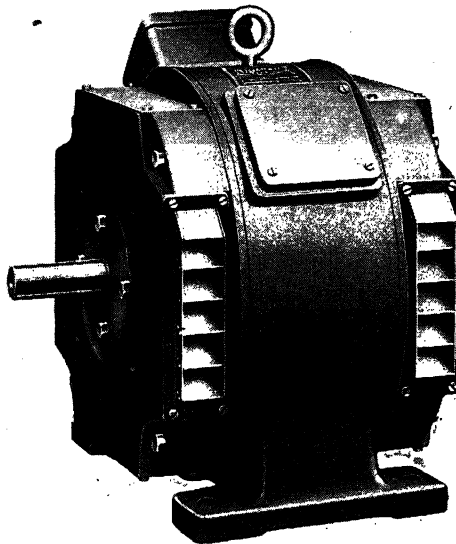


Fig. 177.—20-H.P., 500-V., 750 R.P.M., High-Torque, S.C. Induction Motor.

high-velocity air so that to an appreciable degree the motors are self-cleaning, and that no cement dust may settle in ventilating ducts and windings but may be carried through the machines. A type of motor widely installed on cement works is illustrated in *Fig. 177*.

PORTLAND CEMENT

The higher efficiency and power factor and more robust construction of the squirrel-cage motor makes its adoption desirable for these smaller motors wherever possible. Although special care is required in its application, the squirrel-cage motor has advantages, even on drives requiring heavy starting torques; a full discussion is outside the scope of the present work. The combination of the centrifugal clutch pulley or coupling with the standard squirrel-cage motor appears to be an attractive proposition, but its adoption requires caution.

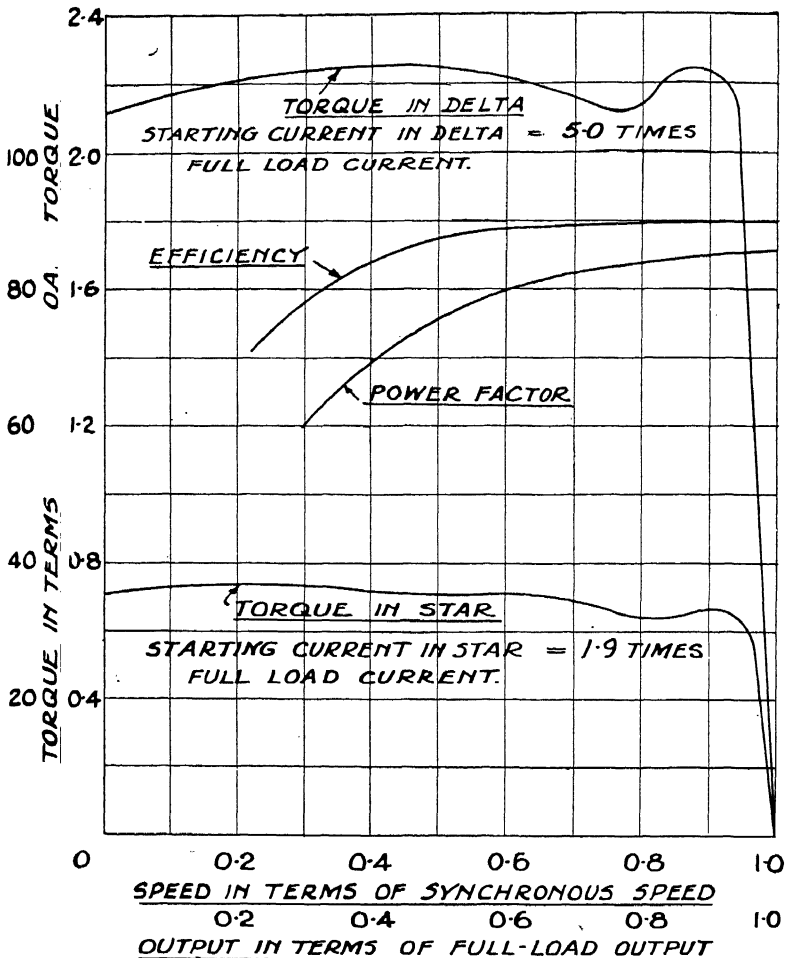


Fig. 178.—Performance Curves of High-Torque Squirrel-cage Motor.

The high-torque machine with the correct method of starting has proved an unqualified success up to 30 h.p. even on heavy starting duties, and its possibilities are indicated by the typical performance curves shown in Fig. 178. Above 30 h.p. the wound rotor (slip-ring) machine should be installed except for light starting duties on account of the excessive starting currents to be dealt with when using the squirrel-cage machine and the expense and difficulty of obtaining suitable standard control gear.

Starters for auxiliary motors will be of the standard ironclad, oil-immersed, industrial type with special provision to render them dust-proof. For overload protection, standard overload trips with or without inverse time lags are usually fitted, but, since motors driving auxiliary machinery are sometimes submitted for long periods to dangerous overloads against which this type of trip affords no adequate protection, thermal relays may perhaps be advocated for this duty.

For slip-ring motors, separate stator switches and rotor starters should be used, the latter being oil-immersed and heavily rated. It will generally be found desirable to have both switch and starter built as one unit suitable for floor mounting. A type of starter suitable for cement works use is shown in *Fig. 179*.

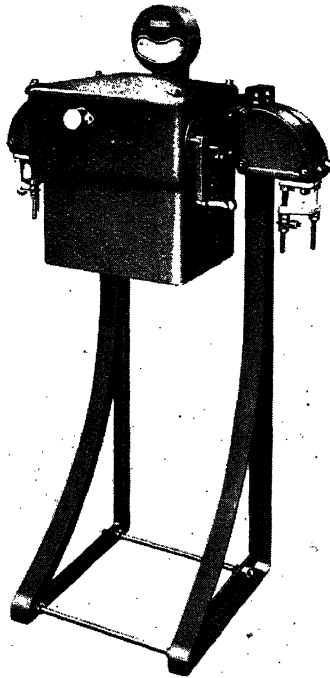


Fig. 179.—20-H.P., 500-Volts, Oil-immersed Star Delta Starter, fitted with Thermal Relay Overload Trips housed in Starter Case.

Reference to the bearings for motors is not out of place in view of the claims made for ball and roller bearings for all sizes and types of machine. Whilst they are strongly advocated for end-shield motors up to 100-h.p., the difficulty of replacing and repairing this class of bearing on large motors must not be ignored. Also, where motors are direct-coupled the difficulty of replacement occasioned by the half coupling is substantial. The best commercial advantage that can generally be claimed for a large ball or roller bearing over a well-designed sleeve bearing is a possible saving on lubrication, which in practice is often found to be more than counterbalanced by other maintenance costs.

For lighting, a 110-volt 3-wire system has advantages in preference to the more usual 200 or 230-volt 4-wire system. This is on the grounds of safety and appreciably

reduced lamp renewals due to the much stronger filament of the lower voltage lamp, accentuated by the very extensive use made of portable lamps in a cement factory.

With a properly arranged scheme, distribution at 110 volts through local transformers fed from a ring main or radial feeders at the primary or secondary pressure can be carried out as economically as at 230-volt, 4-wire. The problems involved in the lighting installations are those common to any industrial plant, but dust-laden atmosphere makes the selection of suitable reflectors a difficult one and in time reduces the efficiency of an installation so that designing for an original illumination of 10 candle-power per square foot for general lighting may be advisable.

Special Applications of Electric Power

Discussion of electrical power as generally affecting the cement industry would not be complete without reference to some of the special applications. The equip-

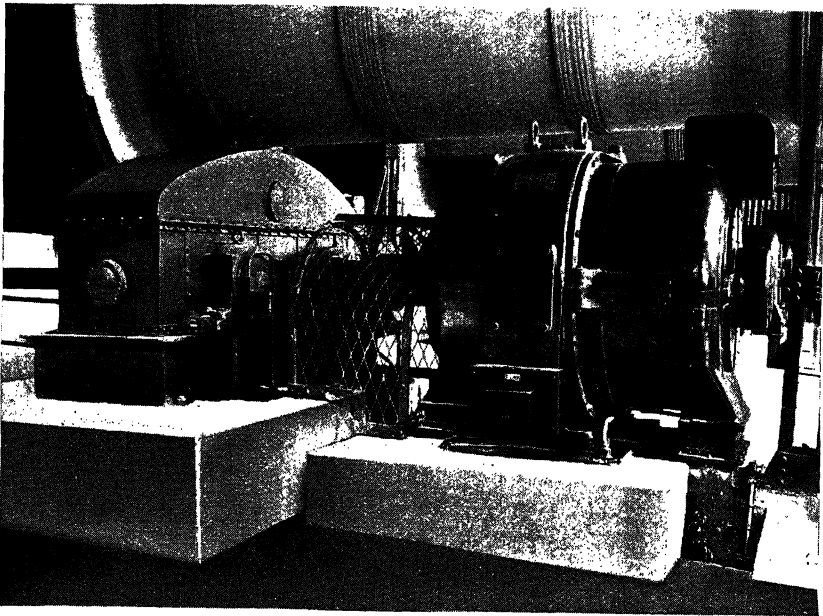


Fig. 180.—40/120-H.P., 230/675 R.P.M., 500-Volts, 3-Phase Commutator Motor, Driving Rotary Kiln.

ment for cranes does not call for comment where a direct-current supply is available. On an alternating-current system, however, advantages are sometimes claimed, particularly on dock cranes, for high-torque squirrel-cage motors over slip-ring machines; but under working conditions the latter have proved a sound commercial proposition.

Each variable-speed drive will call for special investigation on an a.c. system, but the following generally applies for cement works duty. Where the power is not above 100 h.p., and a constant torque at any given speed combined with a large range of speed variation is not required, the less costly and simpler slip-ring motor with rotor resistance will be satisfactory at some loss in efficiency. The same may be said in cases of intermittent duty, but for any power where continuous operation over any speed range and constant torque at any speed are required, the commutator

motor built on the Schrage principle has been found efficient and satisfactory in spite of the appreciably higher first cost. Conversion to d.c. and using d.c. motors may be justified where small powers are involved. Two installations of variable speed a.c. commutator motors are shown in *Figs. 180 and 181*.

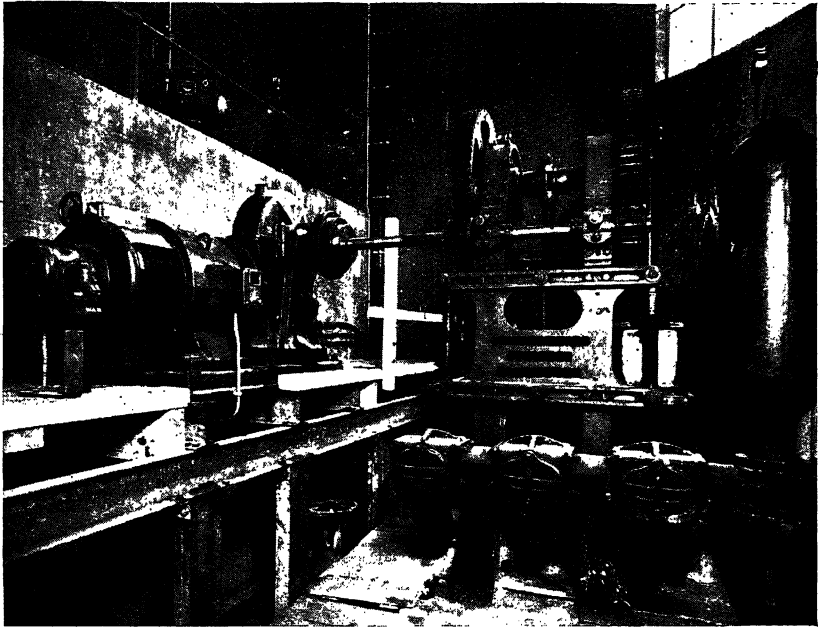


Fig. 181.—12.5/25-H.P., 750/1,500 R.P.M., 500-Volts, 3-Phase Commutator Motor Driving Slurry Pump.

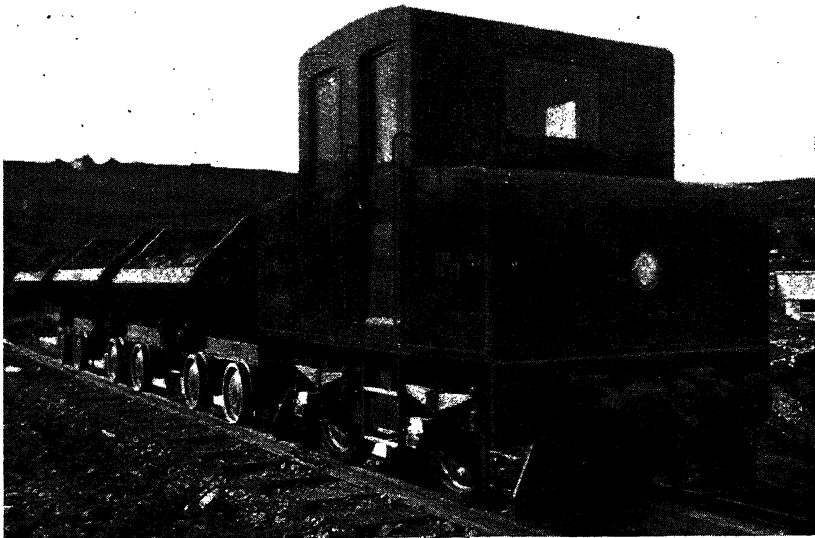


Fig. 182.—Electric Locomotive, 250 Volts, D.C., Hauling Limestone.

Some installations of electric traction (*Figs. 182 and 183*) are in use and giving satisfaction on cement works. On the raw material side, where the bulk of the haulage is required, the site conditions are often difficult, and in many cases roads have to be moved frequently. In addition to this, the use of excavators is very much

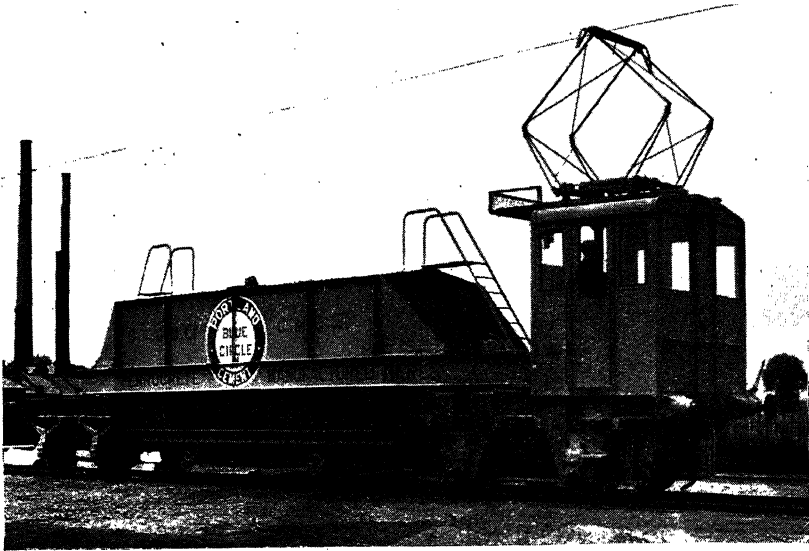


Fig. 183.—15-Ton, 250-Volts, D.C., Electric Wagon for Transporting Cement in Bulk.



Fig. 184.—Electric Excavator. Haulage Winch in Foreground.

against the presence of live rails or overhead wires, while the load is generally intermittent. Electrical power has, however, proved very satisfactory for excavators, and its more general use for this duty can only be a matter of time.

A quarry operated by electricity is illustrated in *Figs. 184 and 185*, the chalk being gained by the $3\frac{1}{2}$ -yard excavator and small winches assisting to form the

trucks into trains. A winch is shown in the foreground in *Fig. 184*, and the 3,000/500-volt transformer with self-contained 3,000-volt and 500-volt switchgear in *Fig. 185*.



Fig. 185.—Electric Excavator. Transformer with Switchgear on Left.

Although electrical power is widely used on cement works with success, and its applications as found to-day have been dealt with, there appears to be no doubt that co-operation between the cement and electrical engineer will lead to the adoption of equipments which will result in higher efficiency and reduced labour costs.

A Modern Cement Works Power House

An interesting example of a high-class English electrical generating station developed entirely for supplying all the power and light required for two modern cement works with a total output of 600,000 tons per annum is illustrated in *Fig. 186*. Originally, the generating plant consisted of one Brush-Ljungstrom turbo-alternator, having a full-load capacity of 3,300 kW. Subsequent developments necessitated the installation of another similar machine, and later a 5,000-kW. Metropolitan-Vickers unit. The supply is 3-phase, 50-cycles, and the pressure of supply was originally 500 volts; but for a total output of 8,000/9,000 kW., for which the completed plant is designed, this would involve handling large currents, and cause considerable difficulties. As part of the power is transmitted to another works nearly a mile away, it was found to be preferable to re-wind the two original machines for 3,000 volts and order the new machine for this pressure. Most of the larger motors operate at the higher pressure, and step-down transformers are used to provide a supply at 500 volts for the smaller machines. The re-winding of the two original sets enabled the output to be increased from 3,300 to 4,500 kW. each.

To supply steam for the increased load, three Babcock and Wilcox marine-type water-tube boilers (*Fig. 187*) were installed, each capable of evaporating 40,000 lb.

of water per hour. Each boiler is complete with superheater and economiser, fitted with the "L" type underfeed stoker and induced-draught fan, and arranged for operating under balanced draught. Forced draught is provided for all three boilers

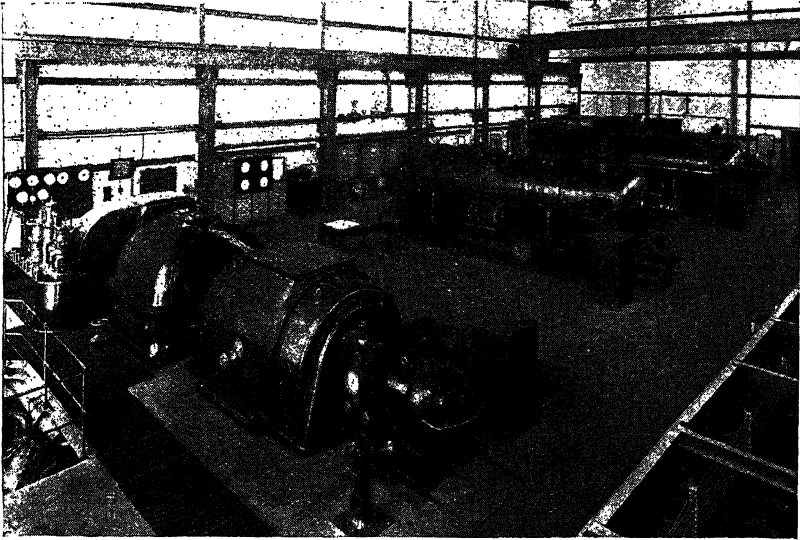


Fig. 186.—Turbine Room at English Cement Works.

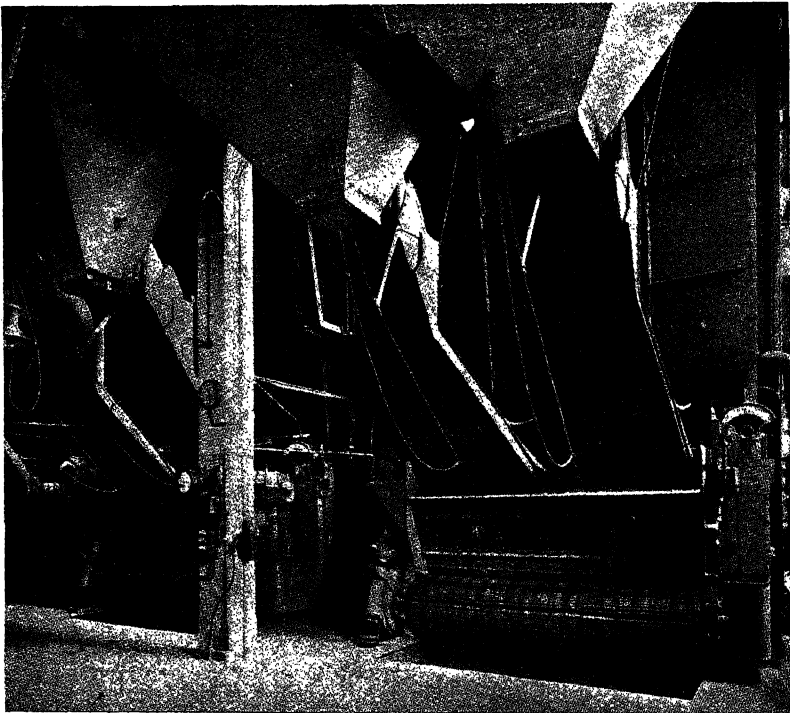


Fig. 187.—Boiler Plant, showing Automatic Stokers, Hoppers, and Chutes.

from a common air duct in which the air pressure is maintained by two Sirocco forced-draught fans, one of which is capable of the duty required for full load conditions. Each boiler unit is fitted with a CO₂ recorder, and also a triple-draught gauge indicating pressures (positive or negative) under the grate, in the combustion chamber, and at the inlet to the main flue, and also a complete equipment of thermometers. The boiler feed is handled entirely by centrifugal pumps, two being rated at 120,000 lb. per hour, and the third auxiliary unit at 80,000 lb. per hour. The boiler feed operates on the closed-feed system, i.e. the feed water never comes into contact with the atmosphere at any time during its complete cycle of circuit between main condenser, feed pumps, and boilers, and thus has no opportunity of absorbing atmospheric gases which would attack the internal surfaces of the boilers.

In order to allow flexibility of operation in the boiler feed system, seeing that both the condensate supply to the feed pump and the demand by the boilers are variable quantities which do not necessarily synchronise, a surge tank has been connected to the feed system between the condensate pump and feed pumps to take care of any difference between supply and demand at the feed pump. The rise and fall of water level in the surge tank are used to actuate the valve that admits extra feed water into the closed-feed system whenever required; this feature is automatic. This system of boiler feeding has been perfectly satisfactory. The following water meters have been fitted: total feed to boilers; feed to low-pressure evaporator; feed to high-pressure evaporator; extra feed water admitted to closed-feed system.

The site of the power house on a river bank is advantageous; a copious supply of cold water for condensing purposes is assured, always at a temperature much lower than could be obtained by the most efficient cooling tower or sprays. The range of the tide is about 20 ft., and the centrifugal circulating pumps are placed at about half-tide level. They are of the vertical-spindle type with motors well above high water. Two of the pumps are rated at 2,400 gallons per minute and two at 7,000 gallons per minute, the latter absorbing about 150 h.p. each. For starting up the pumps at low tide a motor-driven exhaustor evacuates the air from the pump suction line. The plant is designed to give high efficiency at load factors of 70 per cent. and over, and the boiler plant has an efficiency of 71 per cent.

The switchgear consists of a six-panel 3,000-volt switchboard and a ten-panel 500-volt switchboard, both of the cellular type with the stonework cubicles in the basement and the control panels mounted immediately above them on the engine-room floor, the oil switches being remote hand-controlled.

The outlet of the coal chutes to the stokers appears peculiar in *Fig. 187*, but the reinforced concrete coal bunkers were existing, and on account of the increased height of the new stokers it was necessary to put false bottoms in the hoppers and arrange for side discharge of coal as shown.

CHAPTER XVIII

PACKING AND DESPATCH

In modern factories cement is packed in large quantities and at high speed, and this necessitates the rapid handling and accurate weighing of a very large number of separate packages. In no department of cement manufacture have methods been more radically altered and improved during recent years. Until 1914 hand-filling and hand-loading were almost universal. Sacks (made of cloth—no paper then being used) and casks were both filled by hand with shovels, the workers having to work inside the bin of cement. Sacks were loaded into barges and other craft by tipping down a chute, and even for handling the heavier casks, weighing about 400 lb. each, only very simple winches and cranes were used. This, however, must not be attributed entirely to conservatism on the part of the manufacturers. At

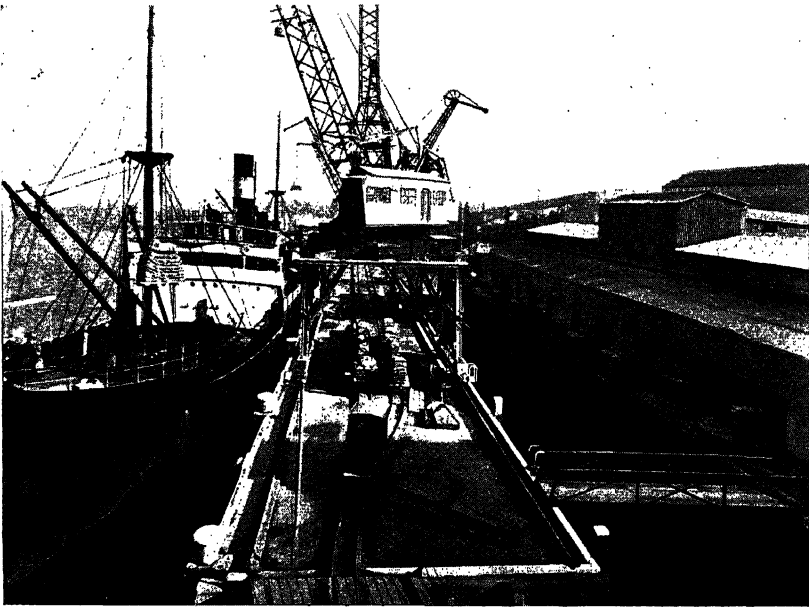


Fig. 188.—Loading Sacks in Slings by Portal Cranes.

that time machines suitable for the difficult conditions had not been perfected, and with the varying requirements of users and the practice of sampling bins at the factory it was found—and this remains true to-day—that the introduction of mechanical plant resulted in a reduction of flexibility. There was then nothing to offset this disadvantage, even on the score of economy, because packing by machine was as costly as packing by hand.

Figs. 188, 189, and 190 show modern methods with large electric portal cranes. The contrast between the old and new methods and working conditions is illustrated by *Figs. 191 and 192*. The former shows casks being filled by hand, the men working in the cement bin and shovelling the cement into the casks, while *Fig. 192* shows the modern system with jolting tables and scales to which the cement is automatically conveyed from the bin.

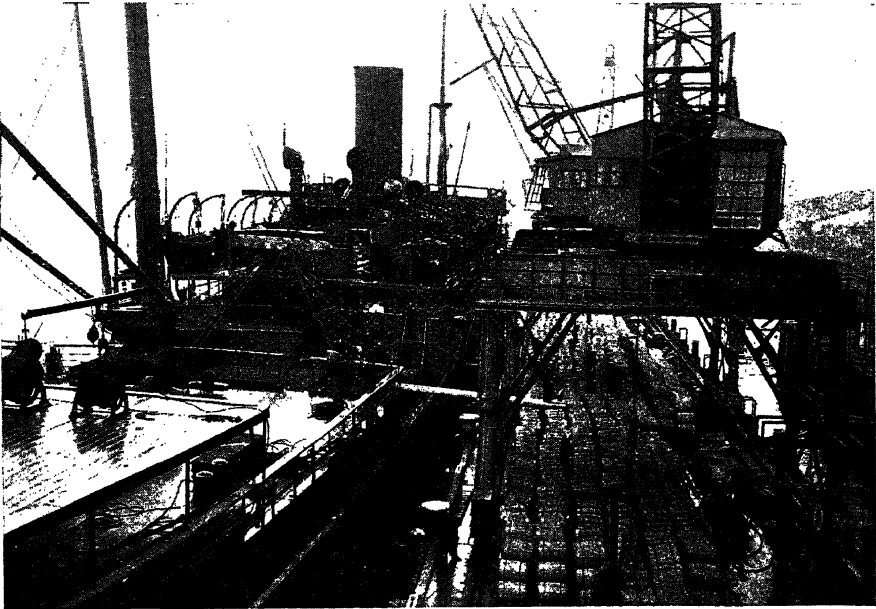


Fig. 189.—Loading Casks by Portal Crane.

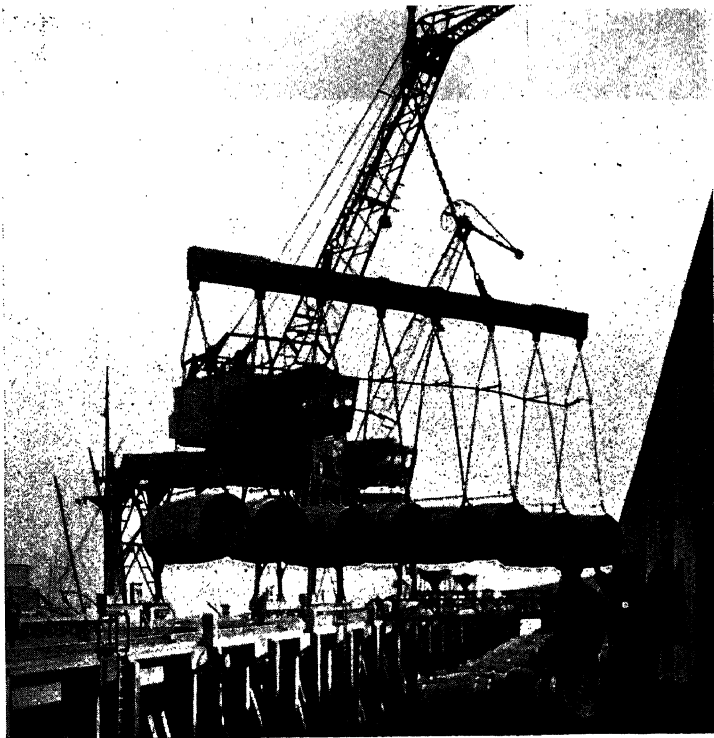


Fig. 190.—Bridle used for Loading Casks.

In a country such as England, with a large export trade to various parts of the world where each market may demand a different form of package, packing machines have to be designed not only to meet the characteristics of cement, but to suit each

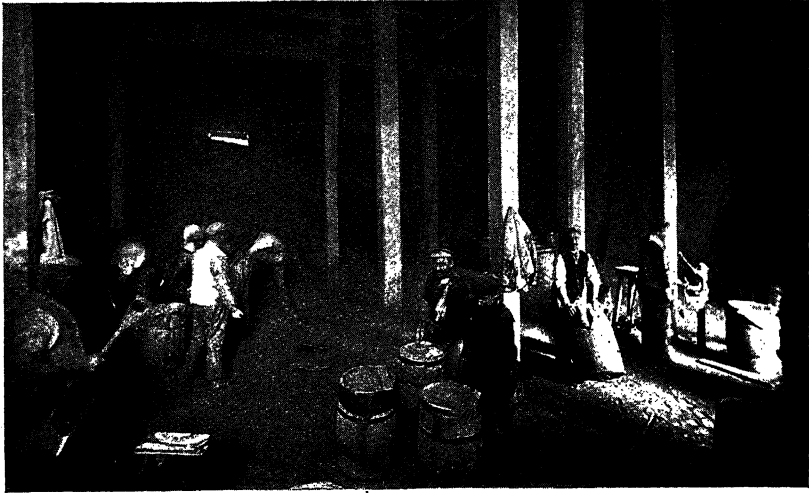


Fig. 191.—Packing Casks by Hand.

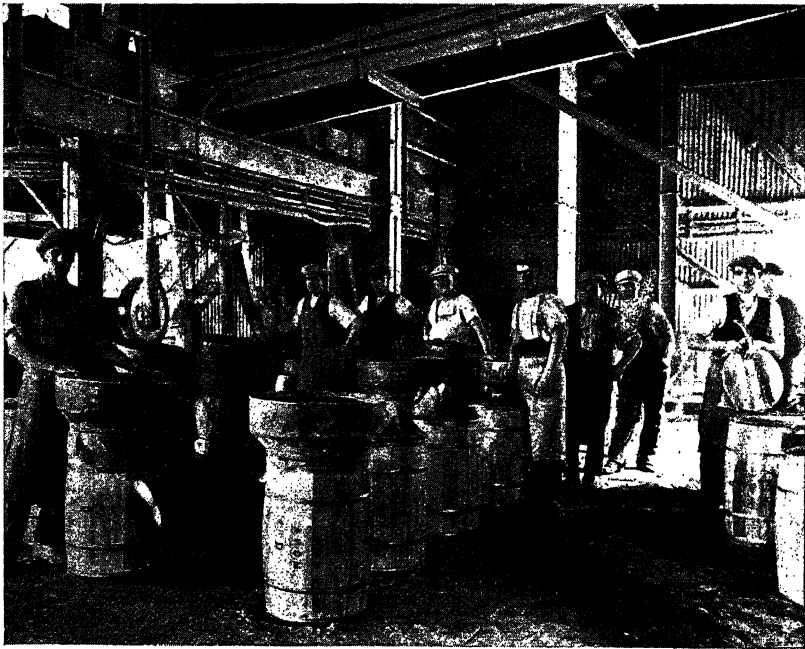


Fig. 192.—Packing Casks by Machine.

type of container used in the trade. These packages comprise jute, cotton, hemp and paper sacks of several sizes, wooden casks, and steel drums. The sacks may be open-mouthed or valved, and the relative advantages of these two types depend

upon several considerations. With hand-filling the open mouth is essential, but mechanical filling led to the introduction of the valve sack. If the valve sack is a comparatively expensive returnable one made of cotton, jute, or hemp, the user has the responsibility of emptying and returning it without damage if he is to recover the sum he has paid for its use. Cloth sacks have been made with a combination of valve and open mouth; the open mouth is tied or sewn at the factory before the bag is filled through a valve, which is formed in one of the bottom corners, and the customer empties the bag by undoing the tied or sewn mouth. To avoid the necessity for a valve in cloth sacks, some packing machines are designed to fill through the open mouth. When non-returnable paper bags are used they can be readily emptied by splitting with a shovel, and no opening is required other than the filling valve.

Filling Valve Sacks

The usual machines for filling valve sacks are those in which a pump is used for forcing the cement through a spout into the sacks, very similar to the centrifugal pump used for water. The diameter of the impellor is comparatively large in relation to the size of the discharge opening, the impellor being 9 in. or 10 in. in diameter and the discharge opening, say, $1\frac{1}{4}$ in. to $1\frac{3}{8}$ in. in diameter. The impellor operates at any desired speed between 1,000 r.p.m. and 1,400 r.p.m. and at an average speed, and with a good depth of cement in the feeding hopper, the usual rate of discharge is 10 lb. or 12 lb. per second.

This type of machine functions by mixing air with the cement, so that the mixture is like a liquid. *Fig. 193* shows a section through the hopper, feeder, and impellor-casing, and the impellor and discharge spout of one of these machines: (a) is the hopper; (b) are the points of application of the compressed air jets to prevent the cement from bridging and to assist it to flow freely; (c) is the feeder-casing with feeder; (d) is the impellor-casing with impellor and driving shaft; (e) is the blade (the wearing element); (f) is the discharge opening of the impellor box which coincides with the similar opening in the spout (g) when pumping is being effected. Cut-off is effected by the vertical displacement of spout (g) relative to the discharge opening in the impellor box. This figure shows the two holes in alignment as they would be when pumping is being effected. *Fig. 194* shows the relative position of these two parts when the sack is full and balance has been effected, the spout (g) having moved downwards.

The Bates machine is made as a two-spout, three-spout, and four-spout unit. Assuming good conditions, it is possible for an experienced operator to pack at an average rate of 30 to 35 tons per hour in sacks on a three-spout machine. One disadvantage of this type of machine is the amount of spillage which takes place at the point where the core of cement leaves the discharge opening of the pump. Normally the cement is pumped through a continuous hole or opening between the pump and the spout, and little or no spillage takes place, but when movement takes place, owing to balance being established, spillage results owing to the broken hole and to the increased space between the faces of the two parts. Spillage also takes place at the moment the filled sack is removed from the spout, and also from within the valve opening of the sack, until the pressure of the cement on the valve closes the hole. A recognised figure for the amount of spillage for these machines is 1 or $1\frac{1}{2}$ tons per hour. The spilt material is usually collected by a spiral conveyor and passed back into the circuit and hopper.

Another type of sack-filling machine for valve sacks is the "Fluxo" packer

originated by Messrs. F. L. Smidth & Co., Ltd. This machine is in no sense a pump, but full advantage is taken of the force of gravity and the liquid properties of a cement-air mixture. The unit "Fluxo" machine necessitates a considerable amount of auxiliary plant, including an extracting screw from the main hopper, a container with orifices and elevator to return the overflow to the hopper, an air compressor with filter, a pulsator for operating the beaters, and a dust-exhausting unit with filters. The machine also has a large number of operating parts. The hopper may

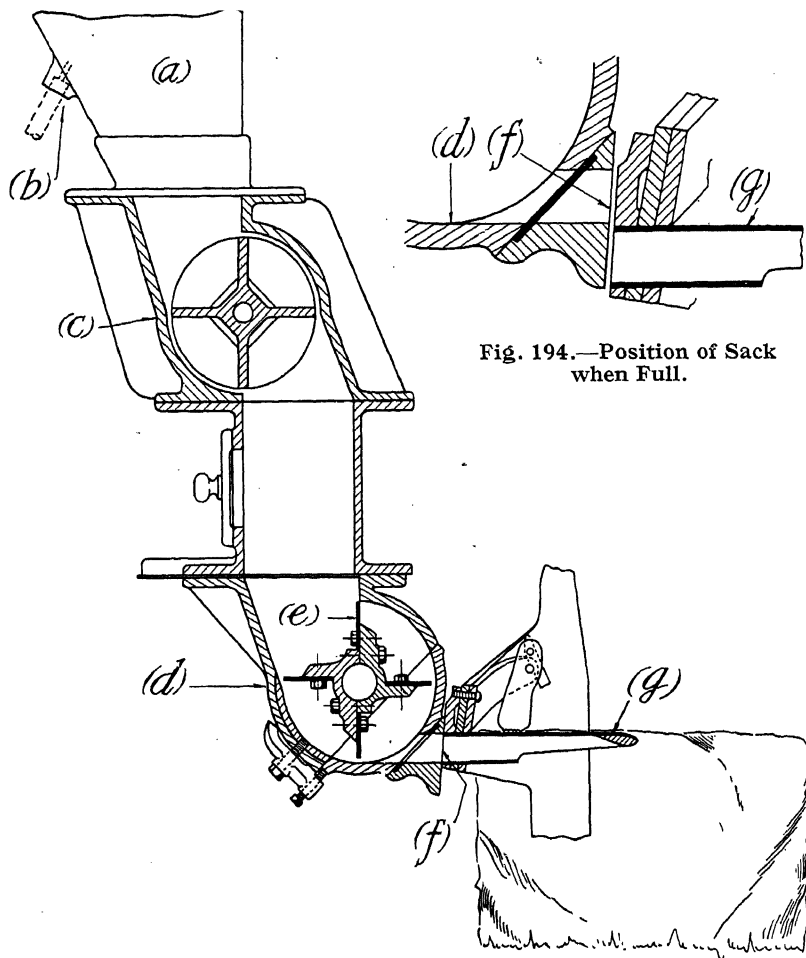


Fig. 194.—Position of Sack when Full.

Fig. 193.—Section of Bates Packer.

have a capacity of up to 15 to 20 tons, depending upon the operating conditions. The hopper supplies the machine through the medium of an extracting screw which conveys the cement to the container at a predetermined rate. This rate is greater than is required by the machine for packing, but it is important to maintain the container full; the excess overflows back to the elevator or source of supply. The container is generally about 5 ft. high, 2 ft. broad, and wide enough to carry the desired number of spouts, usually three. It is fitted with three sets of stirrers. Compressed air is admitted to the bottom of the container through a number of small

nozzles, and the resultant action of the compressed air and stirrers is such that the cement-air mixture in the container attains the properties of a liquid and will flow into the sacks from the container through the orifices, funnels, and spouts. The weighing scale is a dead-weight machine, and the weight of cement on one side must exactly balance the predetermined weight on the other side before a cut-off can be effected. There is a gap between the discharge orifice in the container and the funnelled opening leading to the spout, and any foreign matter or restriction by air

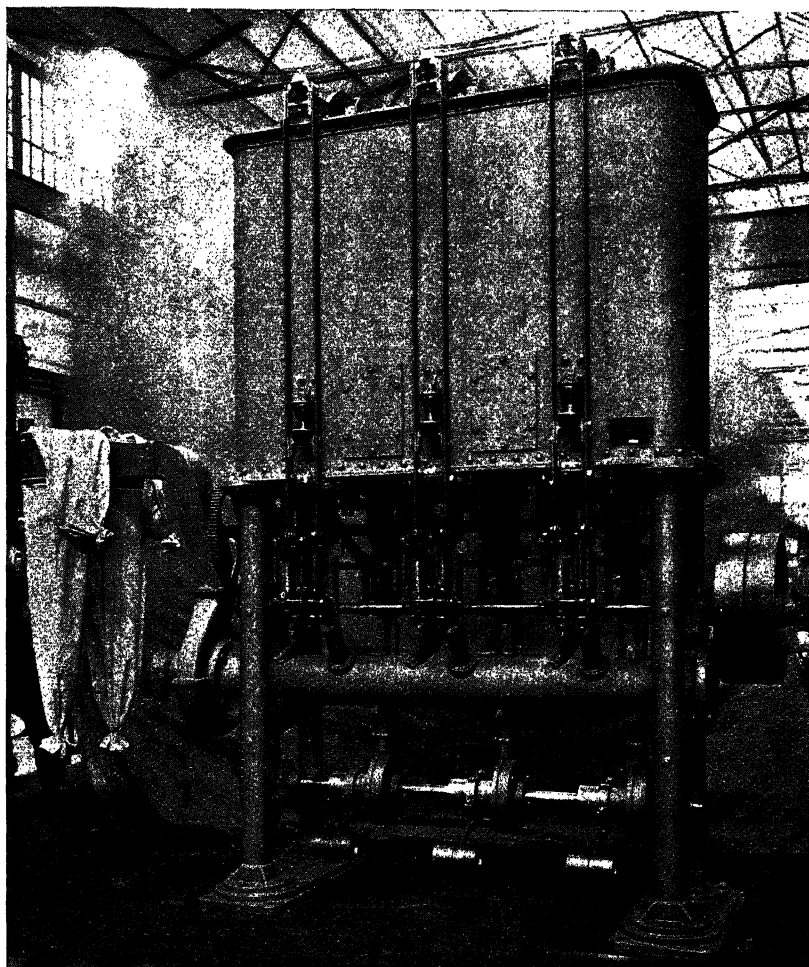


Fig. 195.—“ Fluxo ” Packer.

within the sack or within the spout causes the cement to splash and spill over the edges of the funnel. Spillage also takes place with the release of every sack ; spillage is returned to the circuit and the dust-laden air is exhausted to a filter.

When they flow into a container, ground materials such as cement, coal, gypsum, lime, etc., at first occupy a greater volume than after storage for some time. This is due to the air drawn along with the powder forming voids between the particles. While the material is stored in a container this air slowly escapes,

and the powder falls together and occupies a smaller space. A machine (*Fig. 196*) introduced by a Continental manufacturer, and whose action is based on this fact, is claimed to be the first accurately weighing automatic-filling machine which shakes the sacks while they are being filled, thus rendering possible the use of a shorter sack. The shaking reduces the volume of the cement, and the length of the sack may accordingly be 2 in. to 4 in. less than usual, depending on the increased density of the cement. The possible objection that the sacks will more easily burst is said to be contradicted by experience. The amount by which the length of the sacks may be reduced depends on the density of the particular cement, and is best estab-

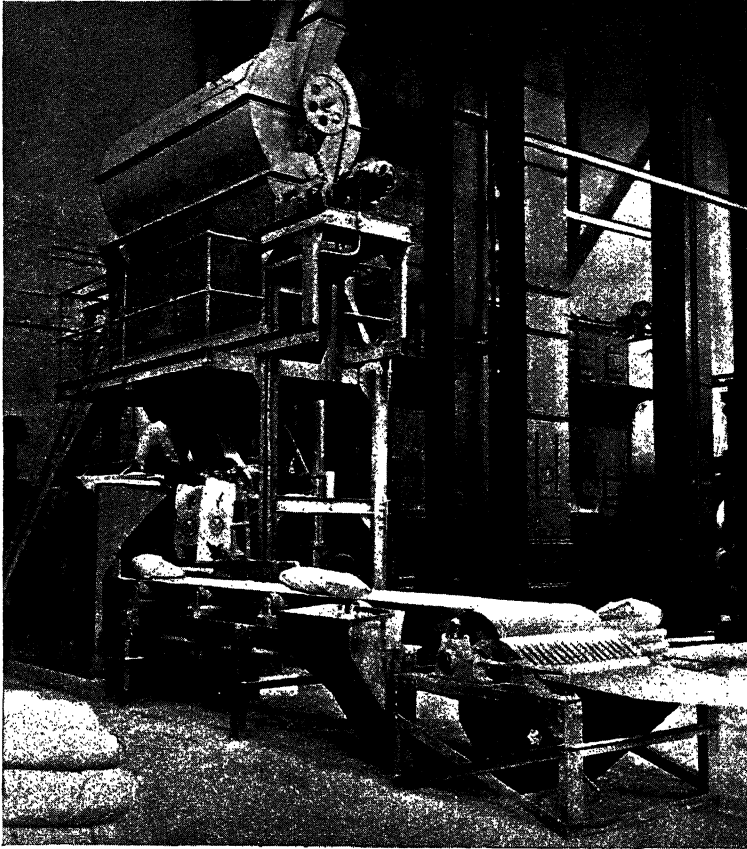


Fig. 196.—Packer with Conveyor Belt.

lished by experiment after the installation of the machine. The length is adjusted so as to allow some margin, and so that some air remains in the shaken cement.

In this type of valve sack-filling machine the cement is conveyed from the silo to a rotary screen fitted with strong steel-wire mesh, which removes foreign bodies from the cement. Below the screen is a distributing screw which delivers cement to the weighing machine below. A precision weighing machine is used which works by weight and not by volume. The dimensions of the container are such that cement of any density can be handled. The weighing machine is contained in a dust-tight enclosure; it is charged first by a main feed and then by a subsidiary feed for fine

adjustment. The cement is discharged by a lower valve, and the attendant has no control over this valve until the charge has been weighed. The number of weighings is automatically registered, and the filled sacks are automatically removed. The inlet and outlet valves are so constructed that no cement can pass through when they are closed. The weighed charge of cement falls from the machine into a funnel below, on to the lower end of which a turbine is screwed. Experiment shows that the momentum of the cement projected into the funnel is almost sufficient to force it into the sack. The filling operation is, however, assisted by the turbine. Since the turbines of the machine only run while the sacks are being filled, and the cement entering the turbine has already an appreciable momentum, it is claimed that the wear and power consumption can only be small. The filling nozzle is screwed to the turbine. Due to the separation of the weighing and filling processes by means of the funnel under the machine, the sacks can be shaken without affecting the weighing.

The nozzles for filling valve-sacks can be unscrewed and replaced by mouth-pieces for filling open sacks. The stand on which the sacks are placed during filling can be adjusted for any length or type of sack. Occasionally torn jute sacks are brought up for filling, the repair of which has been overlooked. The machine is fitted with a contrivance, which can be brought into action at will, for preventing appreciable loss of cement from holes in such sacks. The dust arising from this cause is at once automatically sucked away. This arrangement is rendered possible by the relatively low pressure at which the turbines work. The shaking mechanism is so installed that it can be cut out when it is necessary to fill longer sacks which do not need to be shaken.

Only one attendant is required to operate a four-unit machine. He sits in front of the machine and attaches the sacks to the spouts or nozzles. By moving a lever with one hand, he brings the weighing machine into position for discharging over the sack to be filled. At the same time the filled sack automatically falls away from another spout. The controls are arranged to prevent the operator from emptying the weighing machine before it contains the correct weight. The rate of operation of this machine is stated to be sufficiently rapid to enable a skilled operator to fill 900 sacks per hour. The power requirements of the complete machine, namely, screen, distributing valve, four turbines, and four shaking gears, is 7 h.p. The transmission is entirely incorporated in the machine. The weight per sack is guaranteed to within 7 oz. The accurate working of the machine depends upon (1) the separation of the weighing and filling processes, (2) the use of a precision weighing machine, (3) a plentiful supply of cement to the weighing machine. The overflow due to the copious supply of cement can be led either to the elevator conveying the main supply of cement to the feed silo, or to the storage silo. The latter arrangement avoids over-filling the feed silo. The dust collected can be blown into a silo or a dust filter.

Filling Open-mouth Sacks

There are some good types of open-mouth sack machines, including those manufactured by George Simon, the Bernburger Company, and the "Exilor" manufactured by F. L. Smidth & Co., Ltd.

The Simon machine (*Fig. 197*) has double gates of concave form on the cut-off surface, one of which covers 75 per cent. to 85 per cent. of the opening and the other covers the rest of the aperture. The size, arrangement, and control of the gates facilitate rapid filling during the early part of the operation and a dribble feed for completion and balance. This machine will give consistent results provided the feed

is uniform, filling 8 or 9 tons per hour in 2-cwt. sacks as a single unit and 14 or 15 tons per hour as a double unit.

The double-bag filling machine by the Bernburger Co. (*Figs. 198 and 199*) operates upon the same general principle. In this case, however, the cement is fed to a very small hopper over the machine by means of a spiral conveyor. It is necessary for the quantity of cement passing along the spiral to be uniform, so that the amount in suspension is constant between the spiral and the cut-off flap. Cut-off is effected by two flap-type throw-over valves or shutters, one to control the bulk feed and the other to control the dribble. All moving parts are of light construction and the machine operates with considerable accuracy. This double machine will deal with 12 or 14 tons per hour in 2-cwt. sacks under average conditions. When

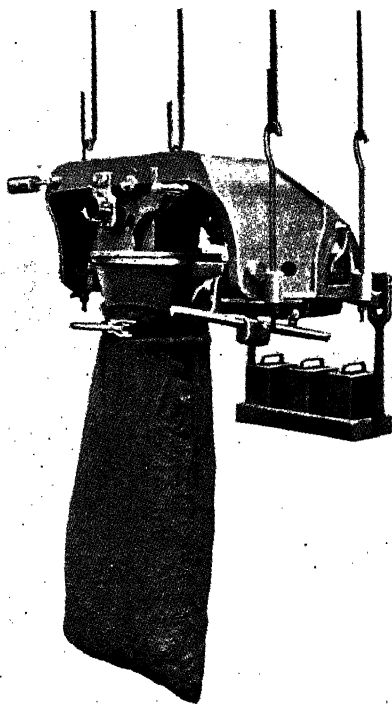


Fig. 197.—Simon Packer for Open-mouth Sacks.

an exhaustor unit is connected to this machine the operating conditions are good and the atmosphere surrounding the machine reasonably clean.

The "Exilor" machine (*Figs. 200 and 201*) is designed for operating in conjunction with silos. It has as a part of its equipment an exhaustor with filter and a somewhat elaborate arrangement of pipes. The suction pipes are inserted in the silos at or near their bottom and connected to the machine, which is a twin-chamber unit. The casing is of cast iron and is fitted with doors having air-tight joints. The pipe from the silo is led to a hood-type casting within the casing. This casting is supported on a scale-beam connected in turn to an air valve on the exhaustor circuit. The empty sack is attached to the hood casting, the casing door closed, and the valve which connects the chamber to the exhaustor opened. The suction effected by the exhaustor through this chamber sucks or draws a mixture of air and cement from the

silo until the sack is full and balance is established. As soon as this takes place the vacuum is automatically destroyed and the supply of cement stopped. One

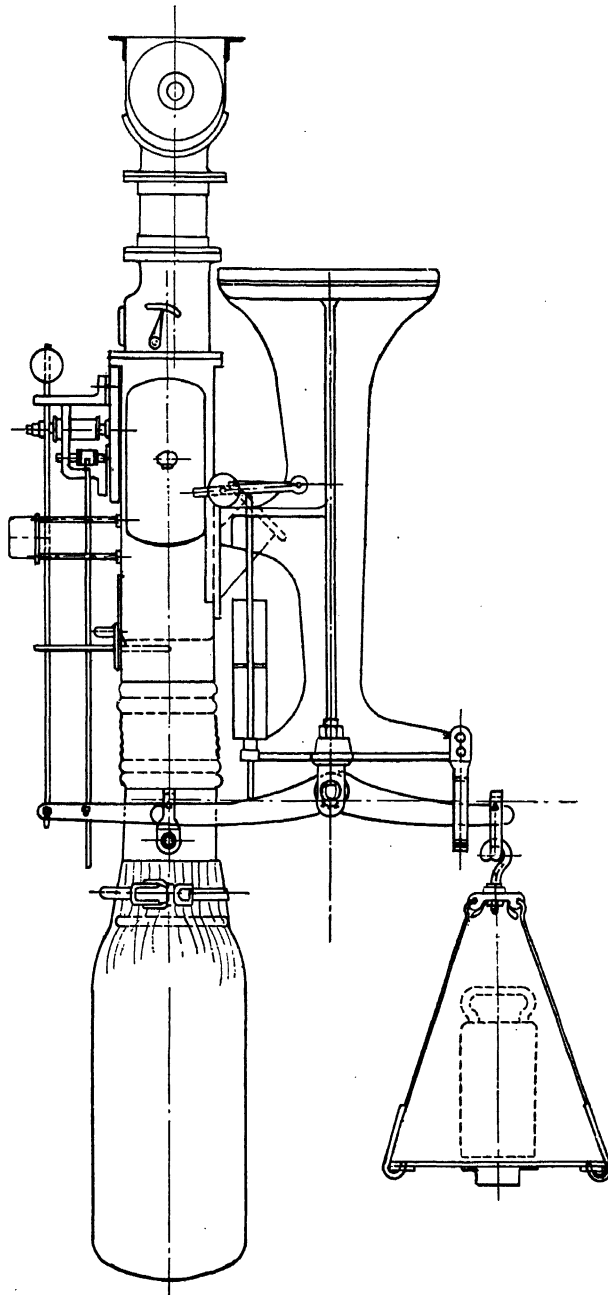


Fig. 198.—Side Elevation of Bernburger Packer.

operator is required for this machine ; while one sack is being filled the other is being changed, and it is possible for one man to attend to the machine and fill at the rate of 15 or 16 tons per hour in 2-cwt. sacks. A small exhausting unit with filter forms

part of the unit. The operation of the machine is clean, and the loss by spillage is negligible. It is also made in a portable form and can be taken at will to any one of

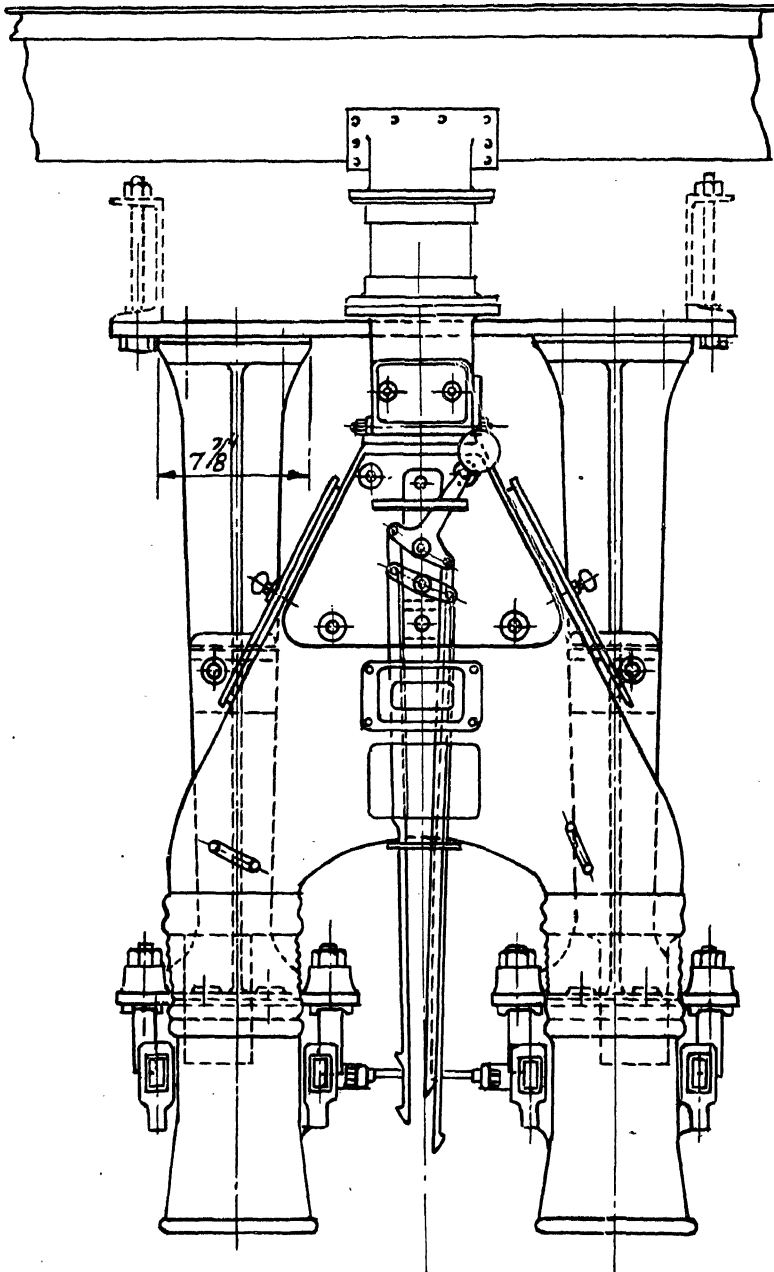


Fig. 199.—Front Elevation of Bernburger Packer.

a group of silos. The power necessary for the operation of the complete unit probably amounts to less than 1 b.h.p. per ton of cement packed.

As has already been mentioned, the mouth or open end of cloth valve-sacks is tied and sealed, or sewn, before the sacks are filled, but all sacks filled at the open

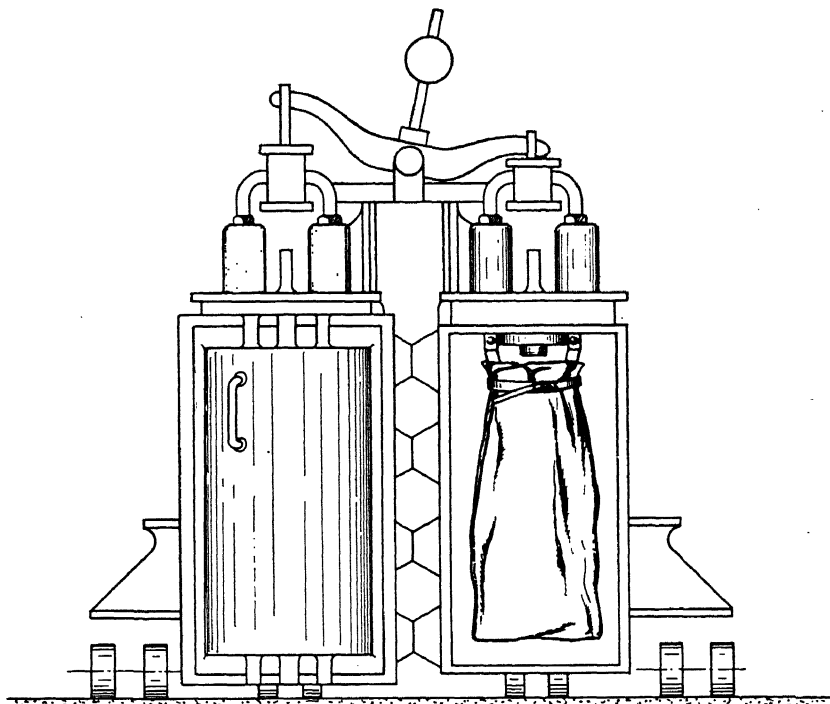


Fig. 200.—“ Exilor ” Packer.

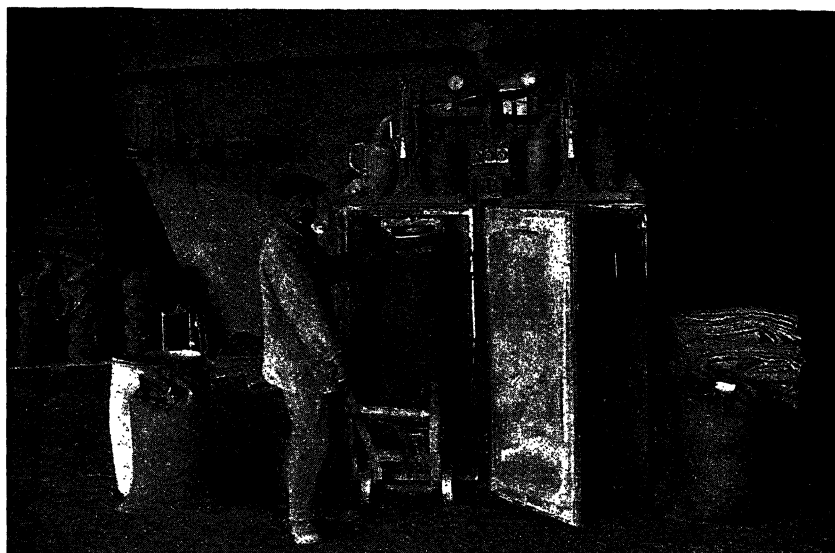


Fig. 201.—“ Exilor ” Packer in Operation.

end are tied and sealed, or sewn, after filling; in every case tying is a separate operation and is carried out by a separate operator. The principles upon which these machines are constructed should ensure accurate weight being obtained from all of them, but the inevitably rough usage to which they are subjected and the rapid rate at which they are operated necessitates a very high standard of upkeep if accuracy of weight is to be consistently obtained.

Filling Casks and Drums

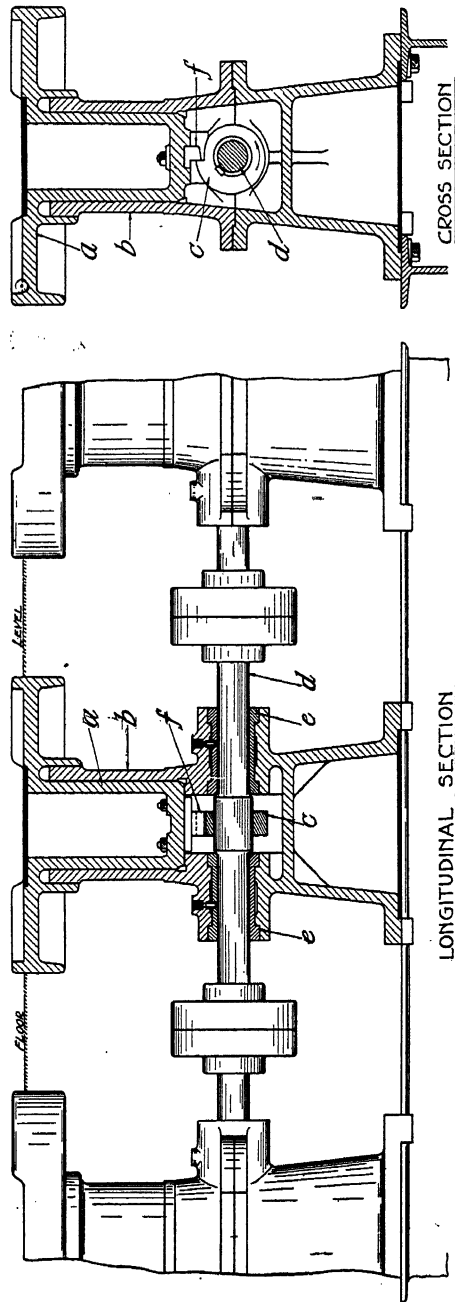
There are a number of machines on the market for filling casks and drums. They all provide good facilities for the escape of occluded air and produce a uniformly tight package. The cask or drum is carried on a rising or falling table which is supported by wire ropes running over guide-pulleys to a heavy balance-weight at the back of the machine. A heavy vertical shaft with a single turn of cast-steel spiral attached to the bottom is placed in the cask with the spiral near the bottom, and the cement fed in. The rotation of this spiral at a slow speed and the pressure it exerts compress the cement and force the cask and table downward against the force exerted by the balance-weight. Thus the cement is packed uniformly tight from the bottom to the top of the cask. After it has been filled the cask is taken to a weighing machine and the weight adjusted. In practice the amount of adjustment found necessary is very small provided appropriate attention is given to the balance-weight on the filling machine. This method is clean, it is easily performed, and results in a minimum of spillage. The power consumption, however, is high.

An alternative method is the use of jarring machines to assist the compacting of the cement. A machine of this type is shown in section in *Fig. 202*: *a* is the table with ram; *b* is the cylinder; *c* is the cam attached to the driving shaft *d* supported in bearings *e*; the cam rubs on the renewable pad *f*. The average period of jarring is three to five minutes according to the fineness of the cement and the degree of compactness required. When this system is adopted it is usual to weigh the cement in a container and empty it into the cask or drum through a comparatively large funnel temporarily fitted to the top of the cask (*Fig. 192*). This funnel holds the excess cement at the beginning of the jarring operation, and as the material is compacted the excess cement finds its way into the cask until the funnel is no longer necessary. Owing to the necessarily easy fit of the funnel in the mouth of the cask, some spillage takes place, and it is difficult to keep the spilt cement from entering the wearing parts of the machines.

In comparing the merits of the screw packing and the jarring methods, it may be remarked that although screw packing is extravagant in power it is clean in operation, and by finally adjusting the weight it produces a package in which the weight, owing to final adjustment, is substantially correct. The alternative system (jarring) is very economical in power, the amount of wear and tear is high, and the weights have to be checked. The ideal system should combine a high degree of accuracy in weighing and low power consumption with a minimum labour requirement and dust-free operation. In practice it is more difficult than might at first appear likely to combine all these qualities in one machine. Nevertheless, the methods adopted to-day may be said to solve the problem within reasonable limits.

A method of pressing the cement into casks and drums hydraulically by means of a ram and cylinder—the latter forming an extension of the cask or drum—has been experimentally tested. Two methods of hydraulic compression were tried (1) by emptying a single-weight parcel of cement into the cask, with extension,

and effecting complete compression in one operation ; (2) by emptying a half-weight parcel into the cask and compressing it and then repeating the operation. So far as pressing is concerned, either or both methods appear satisfactory for the casks,



as these, being more elastic, withstand the local varying pressures better than the drums ; but the drums frequently burst, sometimes down the seams and sometimes down the plain part of the plate.

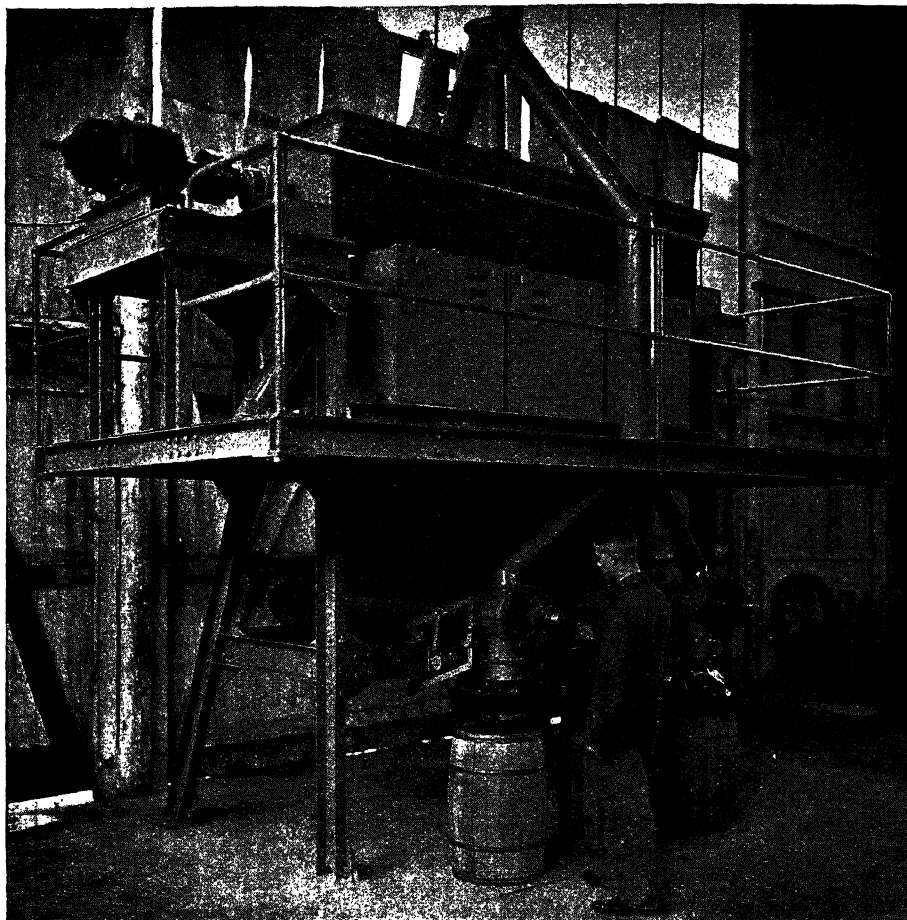


Fig. 203.—“ Andreas ” Cask Packer.

Transporting Packages

When the cement is packed there remains the transport of the packages to the point of despatch and the loading on to lorry, railway truck, barge, steamer, or other conveyance. Every endeavour is made to place the packing machines as close to the despatching point as possible, as the mechanical conveyance of the cement in bulk from the warehouse or silo to the packing machine is a simple operation. It has become standard practice to place sack-packing machines in such a position that the filled and weighed sacks when thrown off the machine will fall on to a slow-running conveyor belt, or gravity conveyor, to deliver at the required height. Installations of this kind are illustrated in *Figs. 204-206*. The conveyor having delivered it to the required point, the bag is put on to the conveyance in one of a number of ways according to the nature of the transport. In its simplest form the operation of loading a lorry with 5 to 10 tons may be accomplished by receiving the bag on an ordinary sack-barrow and depositing it at the desired position on the lorry. Alternatively, an overhead hoist may be used (*Fig. 207*), the slings being left

in position for use at the discharge point, as seen in *Fig. 208*. This method saves labour in suitable cases but requires systematic collection and return of the slings. To avoid damage to paper sacks when they are handled by this method it is preferable to use a board (*Fig. 209*).

Where large quantities of cement in sacks are loaded directly into vessels alongside the works' wharves the conveyors from the packing machines are arranged to deliver to turntables on which the bags are stacked and rotated into a position from which the stack can be picked up by crane and dropped direct into the ship

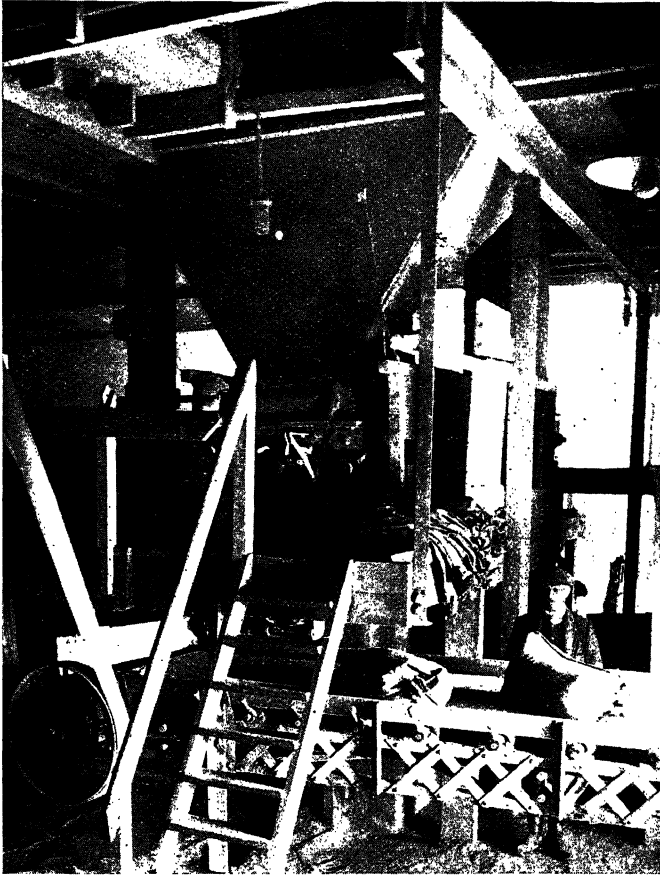


Fig. 204.—Filled Sacks falling on to Belt Conveyor.

(see *Figs. 210-212*). If the cement is packed in casks or drums the packages roll down a gravity conveyor into line on the wharf and are picked up by bridle chains carrying a number of pairs of spring hooks which grip each end of the cask, and the cranes lift whole rows and drop them into place in the ship's hold (*Figs. 213-215*). It is only necessary then for the stowers to handle those casks which have to be placed under the coamings of the ships or in other positions which the crane cannot reach.

Various types of "automatic loaders" comprising combinations having the characteristics of conveyors and elevators are from time to time advocated for

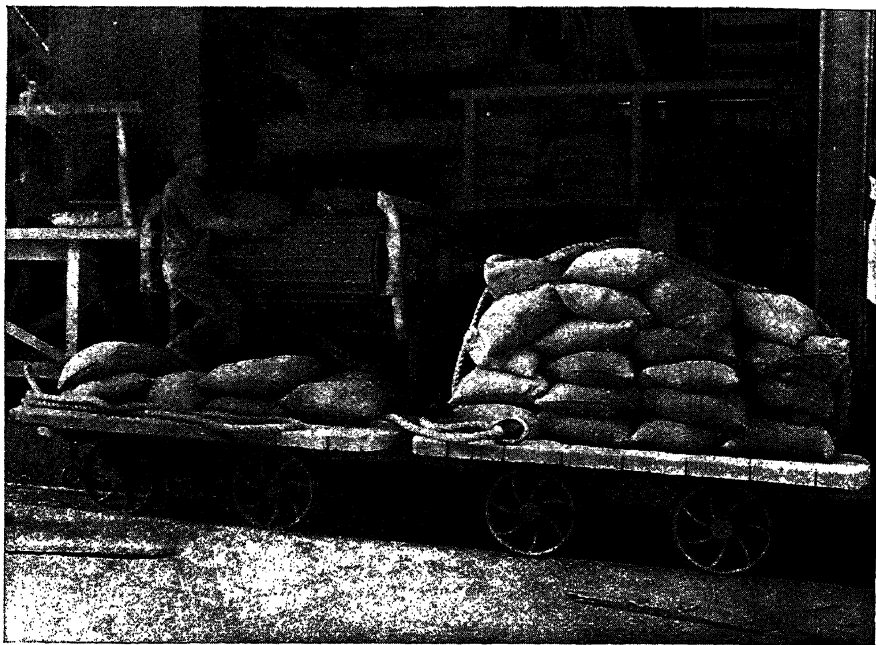


Fig. 205.—Belt Conveyor delivering to Trucks.



Fig. 206.—Belt Conveyor delivering to Turntable.



Fig. 207.—Loading by Overhead Hoist.



Fig. 208.—Cement in Slings ready for Discharge.



Fig. 209.—Paper Sacks slung on a Board.

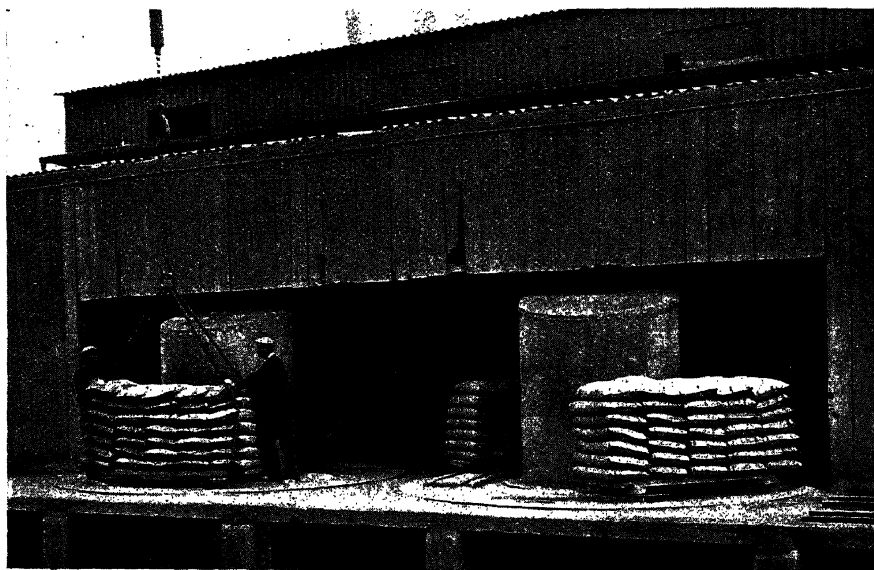


Fig. 210.—Sling being lifted from Turntable by Crane.



Fig. 211.—Sling being lowered into Ship.



Fig. 212.—Stacking Sacks in Ship's Hold.

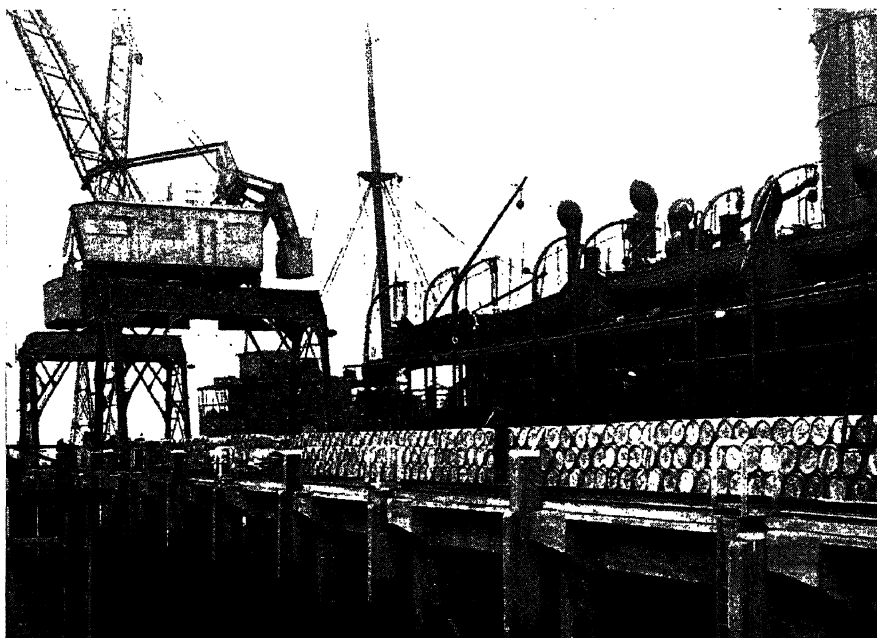


Fig. 213.—Casks ready for Loading.

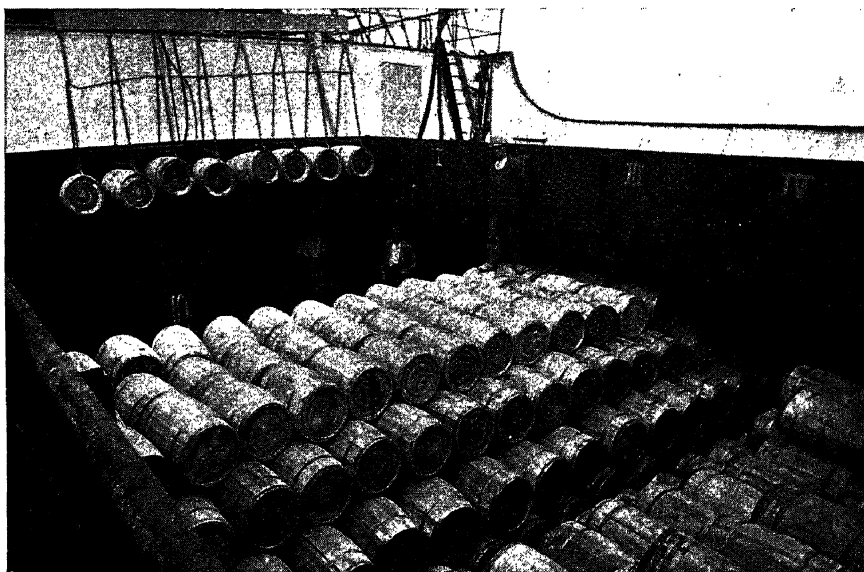


Fig. 214.—Lowering Casks into Ship's Hold.

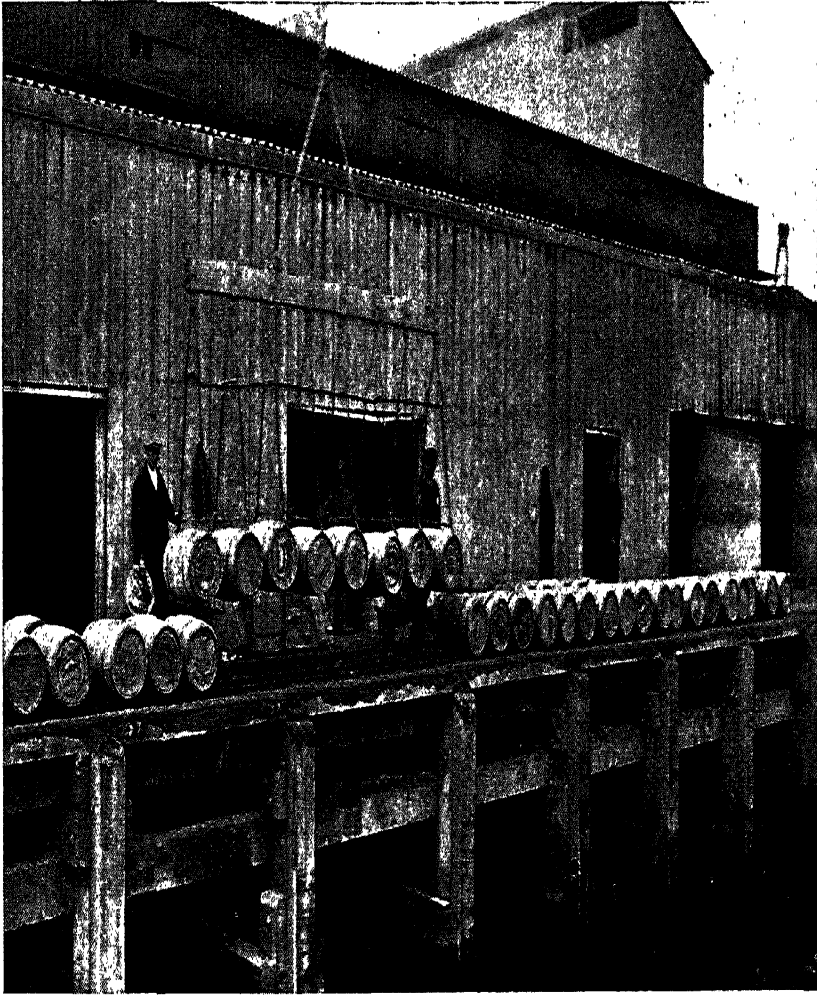


Fig. 215.—Casks Slung and being Hoisted.

cement works, but, for easy and rapid handling of large quantities into craft of all kinds in tidal waters, the electrically-controlled portal crane possesses advantages and flexibility lacking in other machines designed for the same purpose.

CHAPTER XIX

SAMPLING AND TESTING

THE sampling of Portland cement, so that a small quantity shall adequately represent the bulk, is an important preliminary to the carrying out of tests. If the sample is not representative the tests are valueless. Of all engineering materials subjected to a system of testing, Portland cement is probably the most easily misrepresented by improper sampling, handling, or testing. Even in the best equipped laboratories it is impossible to ignore the most important factor—the personal element.

Method of Sampling

In the sampling of cement for the purpose of testing and analysis, the British Standard Specification lays down procedure for avoiding as far as possible the personal equation always evident in sampling bulk quantities. It requires :

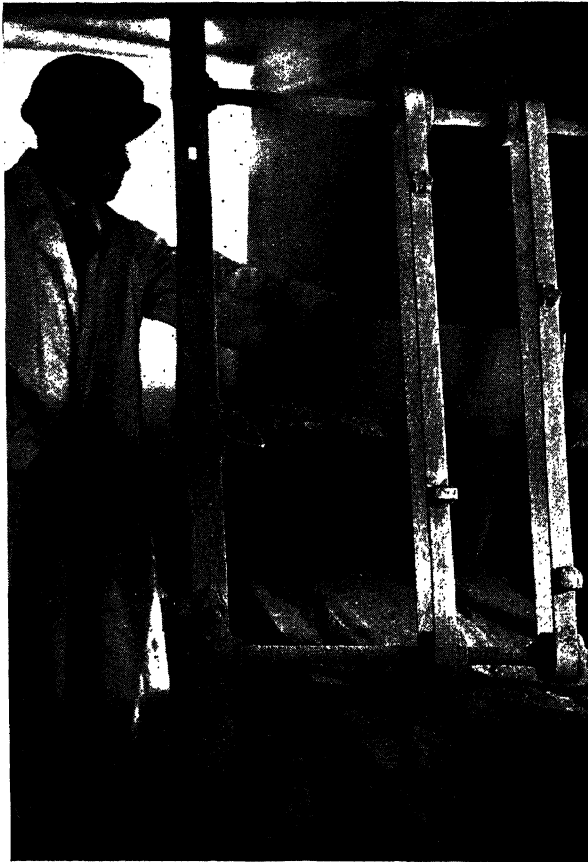


Fig. 216.—Continuous Sampling of Cement from Belt Conveyor.

“ Clause 3.—Each sample for testing shall consist of a mixture of approximately equal portions selected from at least twelve different positions in the heap or heaps when the cement is loose, or from not less than twelve different bags, barrels, or

other packages when the cement is not loose, or, where there is a less number than twelve different bags, barrels, or other packages, then from each bag, barrel, or other package. Every care shall be taken in the selection so that a fair average sample shall be taken. Such final sample shall weigh at least 10 lb. (4.54 kg.).

"Clause 4.—When more than 250 tons (560,000 lb.=254,012 kg.) of cement is to be sampled at one time, separate samples shall be taken, as provided in Clause 3, from each 250 tons or part thereof. Not more than 250 tons shall be stored in such a manner that it cannot be separately identified and sampled in accordance with the provisions of this clause and of Clause 3, and separated in bulk from the remainder. If more than 250 tons of cement is stored in a silo, provision shall be made by which each 250 tons, or any part of 250 tons in excess thereof, shall be isolated from the remainder and sampled at different points." In the case of a silo with a capacity greater than 250 tons, and which cannot be divided, the B.S.S. permits samples to be taken from sampling holes in the walls or at the point of discharge into the silo

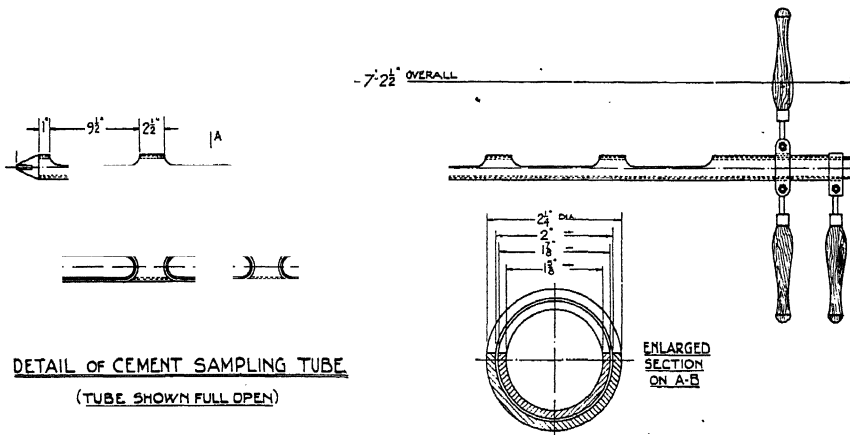


Fig. 217.—Tube for Sampling Cement in Heaps.

provided that the purchaser is satisfied that such samples are representative of each 250 tons.

Obviously a small sample, or even a large one, taken from one place in the manufacturer's store or from one package in a consignment may not adequately represent the bulk, since, due to some local cause, at the particular point of sampling the quality of the cement might be different from the general average. For example, a sack of cement may be damaged by moisture and thus become totally unrepresentative of the bulk.

Cement in barrels can be sampled through a hole made in the centre of one of the staves midway between the heads, or in the head by means of an auger or a sampling iron, but it is preferable to remove the head and take a sample down through the centre. A sample should never be taken from the surface only, but part of the centre should be included, although, in fact, to ascertain as nearly as possible the quality of the cement as packed only the centre should be used. Lumps of cement caused by moisture after filling into bags may move from the outside of the bags towards the centre when the bags are handled, and it cannot be assumed that their position indicates that they were present when the cement was put into the bags.

The necessity for taking small samples from various points of a heap and not merely from the surface cannot be questioned when it is remembered that the latter may have become somewhat air-set by exposure to the atmosphere, and only comprise an infinitesimal part of the bulk, which is more adequately represented by cement obtained from the centre of the heap. This can be done by the use of various sampling devices. One of these (*Fig. 217*) consists of a long tube which is thrust into the heap of cement with the apertures closed. By turning the handle the apertures are opened or closed by an inner tube and cement is drawn up from the heap in positions coinciding with the openings in the tube. The samples drawn from different parts must be thoroughly mixed by turning them over with a trowel after they are spread out upon a table, and it is better also to complete the mixing by passing the sample through a sieve of about No. 30 British Standard mesh. The portion to be used can then be obtained by quartering, in the manner described earlier.

For constructional purposes it is imperative that cement should possess the qualities of strength and soundness, and the primary object of all testing is to determine whether the cement is satisfactory in these two important particulars. The tests for fineness, time of setting, and chemical composition give supplemental information on the probable suitability and durability of the material.

Tests

Soundness is the most essential quality for a cement, and the Le Chatelier test provides a means of measurement which has in practice proved reliable, and erring if at all on the safe side.

In the test for strength, which undoubtedly comes second in importance, we have variations due to the personal equation in mixing, moulding, maturing, and breaking, which make this test dependent upon knowledge and experience and not so susceptible of exactness as might be desired. In testing for setting time, too, these inaccuracies occur, but the fineness test, which is far less important than any of the preceding, is capable of some accuracy, or at least an accuracy that is measured more by apparatus than by long experience in manipulation.

Portland cement becomes progressively more active as the fineness is increased. The clinker itself is inert, and the coarser particles produced by insufficient grinding are of little value except as aggregate. The maximum residue on B.S. sieve No. 170 according to B.S.S. No. 12—1940 is 10 per cent. for ordinary Portland cement and 5 per cent. for rapid-hardening Portland cement. The colour of Portland cement is usually a greenish-grey, but the shade may vary. Other things being equal, the finer cement is ground the lighter the colour.

Portland cement mixed with water forms a plastic paste which subsequently hardens. The time occupied in this hardening is called "setting time." The importance of knowing the setting time of cement lies in the fact that a greater quantity of mortar or concrete should never be mixed than can be used before setting begins. Subject to this essential requirement, the setting of cement is not capable of very precise definition. Neither regulation nor methods of testing are sufficiently exact.

Apart from testing cements by the chemical and physical tests according to well-known standards and theories, the consumer sometimes judges the qualities of cement by so-called "practical" methods, watching the action of cement in work rather than relying upon the qualities as shown by the laboratory records. This has something to commend it, but unfortunately the "practical" test is more likely to give erratic results, and with far more serious consequences, than any of the standard

laboratory tests. There are many ways in which faulty treatment may mar a perfectly satisfactory cement, and there are again many unsuitable aggregates which will spoil work done with cements of proved first-class quality. This may mean disputes between manufacturer and consumer, and, in addition to being extremely unscientific, so-called "practical" tests are fair to neither the one nor the other. In view of the many ways in which unsatisfactory work may arise with a good cement, the manufacturer naturally only assumes responsibility for the quality of his cement, and the consumer is reluctant to accept responsibility for any faulty work carried out with the cement he purchases. The position thus brought about can only be settled to the satisfaction of both parties if there is mutual goodwill and intelligent investigation. Failure in work or in a "practical" test is far more often due to faulty treatment than to faulty cement. While supporting his position by



Fig. 218.—Part of the London Testing Laboratory of the Associated Portland Cement Manufacturers, Ltd.

having samples of the cement tested to the recognised standard of quality or specification, the manufacturer is generally ready and willing to use his knowledge of cement in ascertaining where the fault may be found, which is often in causes which are altogether beyond the control of the manufacturer and have no relation to the quality of the cement. A common cause of trouble arises from the fact that the setting of Portland cement is a chemical process which may be altered or destroyed by unfavourable conditions. Care, experience, and supervision are always necessary in the use of cement, and it is poor consolation for loss to say that the blame for faulty work lies on the cement manufacturer. He now works on much more scientific lines than was the case years ago, and is generally able to make a strong case for the defence where it may be necessary.

Causes of Concrete Failure

The results of a large number of laboratory examinations and analyses of samples of defective concrete have been scrutinised, and have shown that there

are many faults which may cause failure. Some 629 potential causes of failure were found in 353 samples of defective concrete, indicating that in the majority of cases the poor quality concrete had been due not to one adverse factor only but to a combination of factors which together had resulted in concrete so reduced in efficiency as to be the subject of complaint. About 56 per cent. of the faulty concretes was due to bad workmanship in one form or another, and the remainder to faulty materials. The following is a summary of faults found :

(1) Mixtures with too low a proportion of cement, resulting in weak or porous concrete or mortar.

(2) Aggregates contaminated with organic matter, resulting in delayed hardening or failure to harden.



Fig. 219.—Recording Temperature of Cement.

(3) Bad mixing, causing unevenly distributed cement and sand, with separation and bridging of the aggregate.

(4) Sands or aggregates containing excess of loam or clay. The form in which loam or clay is present is more important than the quantity. A small amount of otherwise harmless clay as a film over the aggregate is more detrimental to strength than a larger amount in the form of dry lumps or powder.

(5) Sands too fine, or an excess of fine dust in stone aggregates, resulting in a weak mortar. Only two cases were found in which too coarse a sand had been used without sufficient fine material. The result was a porous concrete with a poor face.

(6) Excessive quantity of mixing water, causing weak concrete, particularly at early periods, with segregation of the mix and contraction cracks.

(7) Incorrect grading of aggregates, including deficiency of intermediate material. In the majority of the cases the aggregates were of unsuitable size for the particular work, causing bad consolidation, porosity, and defective cover for reinforcement.

(8) Over-sanded mixes, resulting in weak concretes owing to the greater surface area requiring more cement.

(9) Under-sanded mixes, resulting in a porous concrete and "bunching" of the aggregate.

(10) Bad workmanship in placing and tamping the concrete, resulting in a loosely consolidated, porous, weak mass. If this type of concrete is reinforced there is a danger of the bars not being properly embedded and covered, with subsequent failure due to structural weakness or rusting of the steel.

(11) Excess of coal in aggregates (breeze and clinker), resulting in expansion of the concrete, with cracking and disruption.

(12) Sulphur in the form of sulphides found in aggregates (spar, unweathered slag, breeze, and clinker) causing delayed hardening and disruption of the concrete on the oxidation of the sulphides. This was frequently aggravated by porous concrete.

(13) Aggregates containing sulphur as sulphates (spar, breeze, clinker, or slags), causing gradual cracking and disintegration.

(14) Faulty curing, such as lack of protection against frost, sun, and drying winds.

(15) Use of flaky aggregate, or aggregate lacking in structural strength or otherwise unsuitable physically (such as soft sandstones and disintegrating igneous rocks).

(16) The action of industrial chemicals to which the unprotected, or insufficiently protected, concrete was subjected.

(17) Aggregates contaminated with gypsum or plaster, such as uncleaned crushed bricks.

(18) Placing concrete in running water as soon as mixed, which washed out some of the cement and sand.

(19) Over-aerated cement due to prolonged or faulty storage, resulting in retardation of the set, and in extreme cases of the hardening also.

(20) Mixing Portland with aluminous cement, causing extremely rapid setting.

(21) Use of too rich a mix or of neat cement, resulting in contraction cracks.

(22) Lack of sufficient cover for reinforcement, resulting in the oxidation and consequent expansion of the steel.

As has been mentioned earlier, in most of the samples of concrete there were found at least two faults, and in many cases there were more than two adverse influences affecting the results.

CHAPTER XX

THE COMPOSITION OF PORTLAND CEMENT

IN discussing the existing theories of the chemical constitution of Portland cement there are two outstanding features which it is necessary to consider in relation to the properties of the raw materials used in manufacture. These are the hydraulic modulus and the silica modulus required in the finished cement. It will be recognised from what has been said earlier that these are fundamental and that a proper determination and control of the raw materials and their mixing are essential if these moduli are to be within the limits necessary for the production of good Portland cement. The hydraulic modulus is a formula which expresses the relation between the basic constituents of Portland cement—such as lime and magnesia—and the acid constituents—iron oxide, silica, and alumina.

In the method of calculation laid down by the 1940 edition of the B.S.S., the magnesia only is ignored, as it is presumed to be in the free state in Portland cement and not in combination with any of the acid elements, such as silica and alumina. The chemical composition as defined in the specification of 1940 is as follows :

“ The percentage of lime, after deduction of that necessary to combine with the sulphuric anhydride present, shall not be more than 2·8 times the percentage of silica, plus 1·2 times the percentage of alumina, plus 0·65 times the percentage of iron oxide, nor be less than two-thirds of that amount. The ratio of the percentage of iron oxide to that of alumina shall not exceed 1·5. The weight of insoluble residue shall not exceed 1 per cent., that of the magnesia shall not exceed 4 per cent., and the total sulphur content calculated as sulphuric anhydride (SO_3) shall not exceed 2·75 per cent. The total loss on ignition shall not exceed 3 per cent. for cement manufactured or sampled or tested in temperate climates and 4 per cent. for cement manufactured or sampled or tested in hot climates.”

The following is an example of the calculation of the lime saturation.

In the case of a cement containing 63·28 per cent. of lime, 21·60 per cent. of silica, 8·15 per cent. of alumina, 2·70 per cent. of iron oxide, and 2·00 per cent. of sulphuric anhydride, the maximum permissible lime is obtained by multiplying the percentage of silica by 2·8, plus the percentage of alumina multiplied by 1·2, plus the percentage of iron oxide multiplied by 0·65, or

$$21\cdot60 \times 2\cdot8 + 8\cdot15 \times 1\cdot2 + 2\cdot70 \times 0\cdot65 = 72\cdot04 \text{ parts of lime for full saturation.}$$

The lime required to combine with the SO_3 is found by multiplying the percentage of SO_3 by 0·7, or

$$\text{CaO for } \text{SO}_3 = 2 \times 0\cdot7 = 1\cdot40 \text{ per cent. CaO.}$$

This is deducted from the total CaO percentage,

$$63\cdot28 - 1\cdot40 = 61\cdot88 \text{ per cent. CaO.}$$

The lime saturation in this cement is obtained by dividing 61·88 by the maximum lime for complete saturation,

$$\frac{61\cdot88}{72\cdot04} = 0\cdot86.$$

It is usual to express the lime saturation as a percentage of the maximum permissible lime, so that the percentage lime saturation of this cement is 86 per cent. The basis for the maximum lime permitted by the 1940 British Standard Specification is given in Lea & Parker's paper,* to which reference should be made as it is too complex to be dealt with in this book.

As a matter of historic interest, a short note on the earlier British Standard Specification No. 12, 1925, is given, and reference is made to the figures in the foregoing example. In the 1925 B.S.S. the chemical composition was defined as follows. "The proportion of lime, after deduction of the proportion necessary to combine with the sulphuric anhydride present, to silica and alumina when calculated (in chemical equivalents) by the formula $\frac{\text{CaO}}{\text{SiO}_2 + \text{Al}_2\text{O}_3}$ shall be not greater than 3 nor less than 2."

The method of calculation is as follows :

Molecular weight of lime	.	= 56
"	" silica	= 60
"	" alumina	= 102

The method of deducting lime for sulphuric anhydride has already been given, the figure for lime in the example, after deduction, being 61.88 per cent. CaO.

The molecular proportions are obtained by dividing the percentages of lime, silica, and alumina by the corresponding molecular weights :

Lime (CaO)	.	$= \frac{61.88}{56} = 1.10$
Silica (SiO ₂)	.	$= \frac{21.6}{60} = 0.36$
Alumina (Al ₂ O ₃)	.	$= \frac{8.16}{102} = 0.08$

Then
$$\frac{\text{CaO}}{\text{SiO}_2 + \text{Al}_2\text{O}_3} = \frac{1.10}{0.36 + 0.08} = 2.50.$$

A convenient approximation to the newer lime saturation percentage can be obtained from the older lime ratio by multiplying the latter by 34, thus :

$$2.50 \times 34 = 85 \text{ per cent.}$$

which is 1 per cent. less than the figure calculated by the new method, but it has been found accurate to about 1 per cent. for nearly all British cements.

The foregoing calculation of the lime ratio shows the proportion (in chemical equivalents) between the lime on the one side and the silica and alumina on the other, and the idea underlying the limits imposed by the older British Standard Specification (viz. 2 to 3) was that a Portland cement should contain at least 2 molecules and not more than 3 molecules of lime to each molecule of silica and alumina. These limits are empirical. The lower limit operates to exclude low-limed cements which are of inferior strength and quality, while the upper limit is a safeguard against an excess of lime which tends to unsoundness. In ordinary practice the limits for the production of good cement are 2.4 to 2.9, and commercial cements

* Lea & Parker. The Quaternary System, $\text{CaO}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{Fe}_2\text{O}_3$, in relation to Cement Technology. Building Research Technical Paper No. 16, 1935.

are usually in the neighbourhood of 2.6. In the production of rapid-hardening Portland cements, however, the methods of manufacture adopted will permit the maximum of 3 with absolute soundness. It is even possible to exceed this figure without unsoundness.

The silica modulus expresses the actual proportion (not in chemical equivalents) between the percentage of silica and the sum of the percentages of alumina and iron oxide, viz.,

$$\text{Silica modulus} = \frac{\text{percentage of silica}}{\text{percentage of alumina} + \text{percentage of iron oxide}}$$

This is important as affecting the quality of the material and also its behaviour while in the kiln. A high silica modulus (i.e. above 2.7) tends to produce a slow-hardening cement, and unless the silica is in a fine state of division there may be a tendency to unsoundness and low strength when mixed with aggregate, both defects arising from incomplete combination between the lime and silica during the burning operation. On the other hand, a low silica modulus tends to produce a rapid-hardening cement which develops its strength at an early date.

In burning the prepared raw materials in the kiln to the point of incipient fusion, materials with a high silica ratio require a high temperature which may increase the fuel requirements and involve undue wear and tear on the rotary kiln lining. Conversely, materials with a low silica ratio—say, below 2.3—clinker more readily, but they tend to form clinker rings which may block the kiln. These lead to serious reduction of output and can only be dealt with by an experienced burner. The ideal silica modulus in Portland cement material is generally agreed to be about 2.5. There are, however, some anomalies which go to show that at extreme limits the rules that have been given do not always apply. Thus, at one works the silica modulus may be very low, viz. 1.7, and yet clinker rings are never experienced, while at another works the silica modulus may be high, viz. over 3.0, with little trouble from wear on brickwork or retarded hardening of resultant cement. The raw materials and fuel used therefore have an important bearing on the results obtained.

The method prescribed in the British Standard Specification for determining the hydraulic modulus is not universally adopted, and in some countries the hydraulic modulus of a cement is calculated differently, namely, by the formula

$$\frac{\% \text{lime} + \% \text{magnesia}}{\% \text{silica} + \% \text{alumina} + \% \text{iron oxide}} = \text{hydraulic modulus.}$$

A figure of 2.2 or higher shows a high-grade cement, while less than 1.8 is not usually permitted.

What is known as the "hydraulic index" of Portland cement is found in the ratio between the silica and alumina (the acid elements) and the lime and magnesia (the basic elements), viz.,

$$\frac{(\text{Silica} + \text{alumina}) \times 100}{\text{lime} + \text{magnesia}} = \text{hydraulic index.}$$

The French Standard Specification limits the lower index to 44, and commercial cements generally show an index of between this figure and 48.

No clear and precise definition of what may be properly classed as Portland cement can be given by specifying the exact raw materials to be used, as various natural formations and waste products have for years been successfully used in

manufacture, and the British Standard Specification contents itself with the following clause :

“ The cement shall be manufactured by intimately mixing together calcareous and argillaceous and/or other silica, alumina, or iron oxide bearing materials, burning them at a clinkering temperature, and grinding the resulting clinker so as to produce a cement capable of complying with this Specification.

“ No addition of any material shall be made after burning other than calcium sulphate, or water, or both.

“ No cement to which slag has been added or which is a mixture of Portland cement and slag shall be deemed to comply with this Specification.”

The term “ artificial ” Portland cement is often used to distinguish cements properly manufactured to this Specification from the “ natural ” cements made in America, Belgium, and elsewhere by the simple process of calcining and grinding natural deposits. “ Artificial Portland cement ” describes a carefully manufactured product obtained from the preliminary mechanical combination of carbonate of lime with silica and alumina as outlined in the foregoing definition. From this it will be understood that the raw material mixing process is essential to ensure accurate and uniform results in the finished cement. “ Natural ” Portland cement is manufactured from mineral deposits having a chemical composition approximating to the percentages needed, but these deposits lack the regularity necessary for consistent quality. The natural deposit is burned as quarried without intimate mixing of the raw materials, and a poor quality product often results owing to the varying composition of the raw materials.

The proportions in which the various constituents are found in Portland cement generally fall within the following limits :

	Minimum		Maximum	
Silica	18	to	25	per cent.
Alumina	3	„	10	„
Oxide of iron	2	„	5	„
Lime	60	„	66	„
Magnesia	0.5	„	4	„
Sulphuric anhydride	0.5	„	2.75	„
Water and carbonic anhydride	1	„	3	„

The limits stated are wide, but this does not mean that a cement is necessarily satisfactory in quality if coming anywhere within them, or that the composition of a cement is in any way immaterial to the results it will give. Different raw materials vary in analysis and composition, and one cement therefore varies in its proportions as compared with another ; but from whatever materials it is manufactured, and by whichever of the numerous processes in use, the analysis of a good quality Portland cement will generally be found to approximate to one or other of the typical examples of British Portland cements given in Table IX.

Notwithstanding the work of many investigators, the constitution of Portland cement is a subject not yet completely understood. Analytical methods have failed, and methods which have been successfully employed in investigating the chemistry of cement are chiefly synthetical and microscopical. By long experience manufacturers are able to deduce from the results of many analyses the safe limits of the essential ingredients, but the manner in which these simple ingredients are bound together and the changes they undergo during the setting of cement are not clear.

TABLE IX.—ANALYSES OF VARIOUS PORTLAND CEMENTS.

	Silica SiO ₂ .	Alumina Al ₂ O ₃ .	Oxide of iron Fe ₂ O ₃ .	Lime CaO.	Mag- nesia MgO.	Sulphuric anhydride SO ₃ .	Insoluble matter, alkalis, loss on ignition, etc.
	%	%	%	%	%	%	%
Cambridge . . .	21.04	5.42	4.50	63.04	0.99	1.81	3.20
do.	20.82	6.57	2.10	64.71	0.99	2.29	2.52
Thames	22.62	5.85	4.45	61.36	0.99	0.97	3.75
do.	20.93	6.10	2.75	64.74	0.93	2.24	2.31
Medway	22.10	7.45	2.57	63.90	1.11	0.77	2.10
do.	20.90	6.26	2.25	64.71	0.87	2.03	2.98
Hull	22.22	7.26	3.97	62.53	1.34	1.86	0.82
do.	20.53	0.45	2.58	64.99	1.30	2.23	1.92
Wales	20.12	6.71	4.03	60.99	2.99	1.89	3.97
do.	20.15	6.17	3.08	63.26	2.17	2.24	2.93
Rugby	21.56	6.36	4.83	62.50	2.36	1.58	0.81
Hartlepool . .	23.30	7.85	4.65	61.90	0.90	1.43	1.97

Many different formulæ have from time to time been put forward as representing a standard composition, only to be contradicted and replaced by others offered by scientists investigating further samples of the material. For instance, Le Chatelier many years ago concluded, after a long study of the composition of cements, that the two important compounds existing in the clinker were a tri-calcic silicate (3CaO, SiO₂) and a tri-calcic aluminate (3CaO, Al₂O₃). Le Chatelier also held that the following maximum and minimum formulæ should usually result in a good cement (1) 2.5 to 2.7, and (2) 3.5 to 4, viz.,

$$\frac{\text{CaO} + \text{MgO}}{\text{SiO}_2 + \text{Al}_2\text{O}_3} = < 3$$

and

$$\frac{\text{CaO} + \text{MgO}}{\text{SiO}_2 - (\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)} = > 3.$$

Conclusions differing from these have since been arrived at by synthesis, and experiments by others as to the constitution of cement have led to the opinions (a) that lime may be combined with silica in the proportion of 3 molecules to 1 and still give a product of practically constant volume of good hardening properties, though hardening very slowly, but that with 3½ molecules of lime to 1 of silica the product is not sound and cracks in water; (b) that lime may be combined with alumina in the proportions of 2 molecules to 1, giving a product which sets quickly but shows constant volume and good hardening properties. With 2½ molecules of lime to 1 of alumina the product was not sound.

Other authorities suggest modifying the Le Chatelier maximum formula and expressing it in weights instead of chemical equivalents as follows:

$$\text{Lime} = \text{silica} \times 2.8 + \text{alumina} \times 1.1.$$

This formula is intended to give the maximum of lime which a cement raw material mixture may contain if the resulting cement is to be sound under ordinary conditions of burning. If we take alumina as 1.0 instead of 1.1 (which makes no

practical difference in the result) we have another formula, or lime factor as it has been termed, thus :

$$\frac{\text{Lime}-\text{alumina}}{\text{silica}} = 2.$$

That is to say, raw material mixtures in which the lime minus alumina divided by silica is more than 2.8 are likely to yield an unsound cement.

On the other hand, for a satisfactory cement this figure should not be less than 2.6 in the raw material mix, and for practical purposes the adoption of 2.7 as a standard lime factor for raw materials is usually satisfactory. Portland cements, as marketed, naturally possess a lower lime factor (lime minus alumina divided by silica) than raw mixtures, generally from 2.5 to 2.6. This is due to the change in composition of the mixture effected during burning by taking up some of the ash of the fuel. In conclusion, it may be stated that the essential and characteristic ingredients of Portland cement are the compounds of lime, silica, and alumina, and that good quality Portland cement manufactured in all parts of the world from different raw materials is of similar composition.

Rapid-hardening Portland Cements

In the production of cement having rapid-hardening qualities, such as are possessed in so marked a degree by high-alumina cements, a considerable amount of progress has been made, but no genuine Portland cement has yet been produced to equal high-alumina cements in strength at early dates. Notwithstanding this difference in early strength, considerably more rapid-hardening Portland cement is being used than aluminous cement, for three reasons: (1) the cost of rapid-hardening Portland cement is very little more than that of ordinary Portland cement, (2) the early strength developed is sufficient to meet the real necessities of most works, and (3) because it is a genuine Portland cement there is not the same feeling of uncertainty as to the permanence of work done therewith.

Cements made with Blastfurnace Slag

These cements are not much used in England, but they can be divided into two main groups, (a) mixtures of blastfurnace slag and Portland cement clinker ground together, and (b) mixtures of blastfurnace slag and lime ground together.

English Portland blastfurnace cement is the subject of a British Standard Specification. This permits of a cement containing an addition to Portland cement clinker of not more than 65 per cent. of granulated blastfurnace slag, the mixture being finely ground. The specification stipulates that it must comply with all the physical tests required of Portland cement.

The German Eisenportlandzement (iron Portland cement) is also a mixture of Portland cement clinker and granulated blastfurnace slag, but limited to the proportions of 70 per cent. of clinker to 30 per cent. of slag. In Germany it is claimed that iron Portland cement is superior to Portland cement for sea-water work, but it may be said that few, if any, works of first-rate importance or magnitude have been carried out in England using cement of this character for making the concrete.

Whereas cements in group (a) are made with a proportion of true Portland cement clinker, those in group (b) are slag cements pure and simple, to which the term "Portland" should never be applied. Their manufacture in England is almost unknown.

Adulterated Cements

Certain mixtures described as "masonry" cements, specially blended to give the qualities considered desirable for masonry and brickwork, are being advocated in some quarters. Qualities sought are workability, adhesion, strength, weather resistance, watertightness, volume constancy, flexibility, and freedom from efflorescence and staining. A notable example is the "low-heat" cement used in a number of large dams in recent years; these cements are specially blended so that the heat of hydration will be low, and thus reduce the possibility of shrinkage and cracking in large masses of concrete.

Many other cements have been patented and produced under proprietary names, many of them claiming improved imperviousness to water when used in concrete.

CHAPTER XXI

THE CONSTITUTION AND CHEMISTRY OF PORTLAND CEMENT

As a result of research work carried out during the past twenty years, commencing with that by Rankin and Wright at the Carnegie Institution in the United States and ending with that by Lea and Parker at the Building Research Station in England, the problem of the constitution of Portland cement has been almost completely solved. It has been established with certainty that well-burned Portland cement clinker consists mainly of tri-calcium silicate ($3\text{CaO} \cdot \text{SiO}_2$), beta-di-calcium silicate ($\beta\text{-}2\text{CaO} \cdot \text{SiO}_2$), tetra calcium alumino-ferrite ($4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$), and tri-calcium aluminate ($3\text{CaO} \cdot \text{Al}_2\text{O}_3$) mixed in various proportions. In some special cements the last may be absent. There may also be accessory compounds such as free lime, free magnesia, alkali compounds, etc., in small quantities.

The microscopical examination of clinker shows it to consist mainly of three distinct substances which are easily distinguished. These were named alite, belite, and celite over forty years ago by Tornebohm, and the problem of the constitution of Portland cement clinker has been to correlate them with the compounds mentioned. Without going into details of a long and elaborate controversy, the following may be said.

None of the separate constituents visible under the microscope in Portland cement clinker are pure compounds. The alite, which is the strength-giving constituent, consists mainly of tri-calcium silicate with an unknown amount of tri-calcium aluminate in solid solution, possibly with a small quantity of an iron compound in addition. The belite consists mainly of beta-di-calcium silicate with an unknown iron compound in solid solution. The celite is actually a complex containing nearly all the rest of the oxides, but consists mainly of tetra-calcium alumino-ferrite and tri-calcium aluminate (when present). When the clinker is very rapidly cooled the celite may not have time to crystallise and may then be present as a glass. In commercial clinkers the celite may be entirely crystalline or entirely glass, or show any stage between these two extremes depending upon the rate of cooling which the clinker experiences after leaving the burning zone.

For given silica and alumina/iron ratios the amount of alite is entirely dependent on the amount of lime in the clinker. Since the alite is responsible for all the early strength and most of the late strength of a cement, the higher the lime content of the cement for given silica and alumina/iron ratios the higher will be its strength. The other compounds contribute little or nothing to the strength, though there is some evidence that beta-di-calcium silicate contributes something to the late strength, e.g. after one month.

The celite portion of the clinker is liquid at the temperature of the burning zone of a rotary kiln and is the medium in which the reactions proceed which produce alite, i.e. the alite forms in this liquid (the flux) and crystallises out from it. The reactions proceed more easily with larger quantities of flux and, since the amount of flux produced increases with decrease in the silica and alumina/iron ratios, cements with these ratios low are easy to burn. If they are too low, however, the amount of flux produced is so large that the clinker is very liquid at the burning zone temperature and difficulties are encountered due to sticking and balling.

The liquid flux can dissolve a limited amount of free lime and free magnesia,

and if the clinker is very rapidly cooled after leaving the burning zone these substances remain in solution in the glass. It has been found that in this state they are not so effective in causing expansion of the cement made from the clinker, hence rapid cooling of clinker promotes soundness in cement. In special cases where magnesia is high, rapid cooling may change a cement which shows late unsoundness (i.e. expansion after one or two years) into one which is satisfactory.

Free lime in Portland cement clinker may be due mainly to two causes, namely, (1) incomplete combination, due to burning at too low a temperature or coarseness of raw material; and (2) the presence of more lime than can theoretically combine with the acidic constituents (SiO_2 , Al_2O_3 , Fe_2O_3).

The degree of burning and the optimum fineness of the raw material depend upon the lime-saturation factor and the silica and alumina/iron ratios. The correct conditions can be arrived at only by experience. The amount of lime which can theoretically combine with the acidic constituents is given by Lea and Parker's formula, which is the limit set by the B.S.S. No. 12—1940 for lime in Portland cement clinker. This is

$$\text{Max. CaO}\% = 2.8 \times \% \text{SiO}_2 + 1.2 \times \% \text{Al}_2\text{O}_3 + 0.65 \times \% \text{Fe}_2\text{O}_3.$$

If the actual percentage of lime in the clinker is divided by the maximum allowable lime content, the lime-saturation factor is obtained.

The three ratios, lime-saturation factor, silica ratio, and alumina/iron ratio, in general govern the quality of the clinker, and any type of ordinary or special Portland cement clinker can be specified by reference to them.

THE CHEMISTRY OF CEMENT

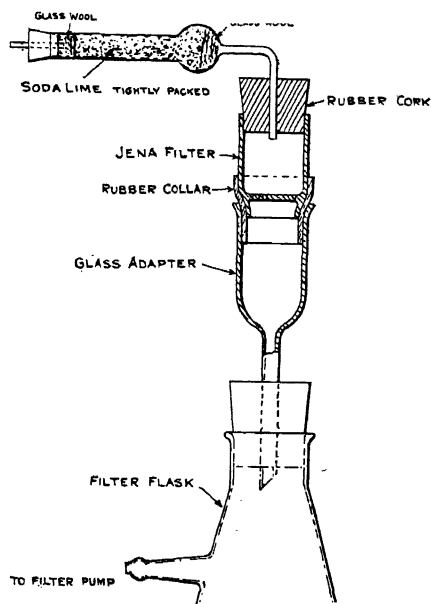
The direct determination of the constitution of clinker is made under the microscope on polished sections of pieces of the clinker which have been etched by suitable reagents in order to bring out the structure. A series of imaginary lines is taken on the section and the lengths of the intercepts of each constituent on these lines are added together. Since these sums are proportional to the volumes of the components the percentage constitution can be calculated, because the specific gravities are known. In practice the imaginary lines on the slide are defined by one of the cross-wires of the microscope, and instead of writing down and adding together the different intercepts an integrating stage is used on the microscope which does this automatically.

Unfortunately at the present time it is not practicable to use this method on cement works. One may, however, visualise in the future each cement works having its microscopes and other scientific equipment, with skilled operators who would furnish the manager with full descriptions of the chemical constitution of the clinker produced on the works and with advice on the procedure to be adopted to prepare cements to suit the different requirements of cement users. Up to the present the works chemist has controlled the product by chemical analysis only, although there is now a tendency to calculate the compounds present in the cement from the chemical analysis by the method given by Lea and Parker and referred to in Chapter XX. By this method the chemist can report the content of the clinker samples of each of the following compounds: Tri-calcium silicate ($3\text{CaO} \cdot \text{SiO}_2$), di-calcium silicate ($2\text{CaO} \cdot \text{SiO}_2$), tri-calcium aluminate ($3\text{CaO} \cdot \text{Al}_2\text{O}_3$), tetra-calcium ferro-aluminate ($4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$), magnesium oxide (MgO), free lime (CaO), and occasionally penta-calcium tri-aluminate ($5\text{CaO} \cdot 3\text{Al}_2\text{O}_3$).

The main strength-giving constituent is $3\text{CaO} \cdot \text{SiO}_2$, and minor ones are $2\text{CaO} \cdot \text{SiO}_2$ and $4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$, while $3\text{CaO} \cdot \text{Al}_2\text{O}_3$ is injurious if present in large quantity, say, over 12 per cent. MgO may affect the soundness of cement, and the amount is limited to 4 per cent. by B.S.S. No. 12—1940.

The properties of cement are in general influenced by the percentages of the calculated components and, if it is possible to vary the analysis of the raw material, cements can be produced having special properties, such as sulphate resistance, low-heat evolution for large mass concrete structures, and special cements for oil wells. Rapid-hardening cements are also within the control of the chemist, but in this case the fineness of the cement is usually a more important factor than the chemical constitution.

By Lea and Parker's method a fairly close approximation to the actual constitution of the clinker can be obtained, but the constitution is affected by the rate of cooling the clinker, so that the method is open to criticism. This method is,



APPARATUS FOR DETERMINATION OF FREE LIME IN CEMENT.

however, the best available at present and is very useful in spite of the difficulty in relying absolutely on the results given by the method.

As already stated, the method of controlling quality is derived from inspection of the simple analysis of the cement or clinker, in which the constituents are stated as oxides. B.S.S. No. 12—1940 gives certain limits of these constituents, and this is a guide to the chemist. The percentage of lime (CaO) is the most important, as very slight variations in the percentage of lime have marked effects on the quality of the cement. It is now not considered sufficient to determine only the total CaO in cement; it is essential to know how much of the CaO is free (i.e. present as CaO) and how much is combined, as in the lime silicates, aluminates, etc. The best method of determining free CaO is as follows:

The maximum CaO content is limited to the amount of CaO given by the equation

$$\text{Max. CaO}\% = 2.8 \times \% \text{SiO}_2 + 1.2 \times \% \text{Al}_2\text{O}_3 + 0.65 \times \% \text{Fe}_2\text{O}_3,$$

and the total lime-saturation in a cement is obtained by dividing the total CaO in the analysis (less CaO combined with SO_3), by the maximum CaO obtained by the equation, and multiplying by 100 so as to state the saturation as a percentage of the maximum permissible.

It is also advisable to determine the saturation of the combined portion of the CaO in the analysis. In this case the free CaO as well as the CaO for SO_3 is deducted from the total CaO before calculating the combined CaO saturation in the same way as for the total lime saturation.

The minimum total lime content, after deducting CaO for SO_3 , is limited to two-thirds of the maximum given by the equation. It may perhaps here be mentioned that the maximum CaO allowed by B.S.S. No. 12—1940 is slightly too low. The equation is correct according to theory for combined lime, but it is known that free CaO is usually present in amounts up to 1 per cent. and at this amount is not injurious to cement.

Other items subject to limitation by B.S.S. No. 12—1940 are : MgO is limited to a maximum of 4 per cent. ; SO_3 to 2.75 per cent. ; insoluble residue to 1 per cent. ; and the loss on ignition to 3 per cent. in temperate climates and to 4 per cent. in hot climates.

The methods used for the analysis of cement and clinker are as follows.

Determination of Free Lime.

When the free lime in clinker exceeds 1 per cent. the causes are either that the lime in the slurry is too high, or that incomplete combination is taking place in the kiln. In the first case the effect of high free lime in clinker will be unsoundness. In the second case the effects are unsoundness and loss of strength, because every 1 per cent. of free lime reduces the alite by about 4 per cent. Alite is the strength-giving constituent, and is usually present in amounts of from 50 per cent. to 70 per cent. Another effect of high free lime in clinker is that the clinker falls to pieces, if not to dust, on storage.

In the case of cements the meaning of free lime is not so clear. During grinding the clinker is exposed to the atmosphere which contains water vapour and CO_2 , and also to water vapour from gypsum which is liable to dehydrate in the mill. The absorption of water by the clinker results in the liberation of free $\text{Ca}(\text{OH})_2$ from the $3\text{CaO} \cdot \text{SiO}_2$, and this tends to yield a higher percentage of free lime than the original clinker. CO_2 , on the other hand, forms CaCO_3 with free $\text{Ca}(\text{OH})_2$ and tends to lower the free lime content. In cements, therefore, high free lime cannot necessarily be attributed to either excessive lime in the slurry or incomplete combination in the kiln.

For these reasons the free-lime test should be carried out on clinker and not cement. The difficulties of obtaining an average sample are recognised, but if sufficient time and care are given to sampling the results should be satisfactory, and would certainly be more satisfactory than if cement was used for the test. The average clinker sample should be ground, preferably in a small mill, until it passes B.S. sieve No. 200. The time during which the clinker is exposed to the atmosphere in the grinding operation should be reduced to the minimum to avoid absorption of moisture and carbonation.

REAGENTS—(1) $\frac{\text{N}}{10}$ *Hydrochloric Acid*.—Approximately 20 ml. of concentrated HCl are made up to 1 litre with distilled water. About 0.2 gr. of freshly-ignited A.R.

sodium carbonate is dissolved in about 150 ml. of distilled water in an Erlenmeyer flask and four drops of methyl orange indicator are added. The solution is then titrated with the acid. The acid will be above N/10 strength and will require dilution. This is done in two stages as follows: Let W = weight in gr. of sodium carbonate taken, A = ml. of acid used in the titration, and V = ml. of acid left in the stock bottle. The amount of water to be added to bring the solution nearly to N/10 strength is

$$\left(188.7 \frac{W}{A} - 1.05\right) V \text{ ml.}$$

The titration against sodium carbonate is repeated on the diluted solution and fresh values for W , A and V obtained; call these W_1 , A_1 , V_1 . The amount of water to be added to bring the solution exactly to N/10 strength is

$$\left(188.7 \frac{W_1}{A_1} - 1\right) V_1 \text{ ml.}$$

The test is repeated to make certain that the solution is exactly N/10 strength. When this is so, W gr. sodium carbonate will be exactly equivalent to $188.7 \times W$ ml. acid, which is the same as saying that 1 cc. = 5.3 mg. Na_2CO_3 . Hence 1 cc. of acid = 0.0028 gr. CaO .

(2) *Methyl Orange Indicator*.—0.1 gr. of methyl orange is dissolved in 100 cc. of industrial or absolute alcohol.

(3) *Absolute Alcohol*.—This should contain approximately 99.5 per cent. ethyl alcohol. It absorbs water readily from the atmosphere and should be kept in a glass-stoppered bottle provided with an airtight rubber cover made from wide-bore rubber tubing slipped over the neck and stopper. Alternatively, a rubber cap such as is used for covering serum bottles is suitable if the right size can be obtained. Glass stoppers are not generally airtight.

Ethylene Glycol.—It is important that this reagent should be chemically pure and as anhydrous as possible. It absorbs moisture readily from the atmosphere, and the bottle should be protected as for absolute alcohol. The stock bottles should be sealed with a 50/50 resin/beeswax cement. The neutrality of the glycol is determined as follows. Add four drops of methyl orange indicator to 40 ml. of glycol, when a bright straw yellow colour will result. Titrate with N/10 HCl until the colour changes to orange pink. The amount of HCl required must be deducted from the amount of HCl used in a free-lime determination before calculation of the latter. The moisture content of the ethylene glycol is best tested by measuring its specific gravity with either a Westphal balance or a hydrometer. The following are the lower limits allowable for specific gravity:

Temperature (deg. C.)	Specific gravity
10	1.1,200
15	1.1,175
20	1.1,145
25	1.1,125

METHOD.—0.75 gr. of the sample is weighed into a clean dry 200-cc. flask. Half a teaspoonful of dry washed standard sand is added and mixed with the sample; 40 cc. of ethylene glycol are added and the flask swirled to mix the contents completely. The flask is corked and placed in a water bath which is maintained between 150 deg. and 160 deg. F. for 30 minutes. Every seven or eight minutes the contents

of the flask are shaken. The liquor is now filtered through a Jena I.G.3 sintered filter with the help of suction. If Jena sintered glass filters are not available, a Gooch crucible containing two superimposed circles of Whatman No. 42 filter paper cut to fit the crucible is satisfactory. The paper is moistened with glycol and filtration is carried out under a fairly high suction. Except when liquid is poured on to the filter the latter is kept closed by a rubber cork which is fitted with a glass U-tube or trap containing fresh soda-lime. The use of the soda-lime trap is important, for if it is not used and a long time is spent over filtration the result may be low owing to carbonation. The cork must not be wetted by the filtering liquid. When all the liquid has been filtered the flask is washed three times with 8 to 10 cc. of absolute alcohol. When all the washings are filtered the Jena filter is removed, four drops of indicator are added, and the liquid is titrated with N/10 HCl from a bright straw yellow to an orange pink.

It is not difficult to check this method of free lime determination by the following procedure. The principle is to titrate a small quantity of pure CaO under the same conditions as the test for free lime. The amount of CaO found by titration should, of course, be the same as the amount weighed out in the first instance.

The procedure is to weigh a small quantity of dried A.R. CaCO_3 (say 45 mg.) into a platinum crucible. The crucible is then heated at 1,000 deg. C. for 30 minutes. It is then removed quickly from the furnace and placed in a desiccator containing dried silica gel or phosphorus pentoxide (CaCl_2 is unsuitable). As soon as the crucible is cool enough to be handled it is removed from the desiccator and the contents brushed quickly into a flask containing 40 ml. of ethylene glycol and the flask corked with the soda-lime trap. The flask is then heated and stirred as described in the method. After cooling to room temperature the contents are titrated with the N/10 HCl solution as in the method. The amount of N/10 HCl should be 9 ml. after the neutrality correction has been applied. The tolerance is about ± 0.25 ml. of acid, i.e. the equivalent of ± 0.1 per cent. of free lime on the assumption that 0.75 gr. of clinker had been used.

If it is consistently found that the amount of CaO by this test differs from the weighed quantities by more than this tolerance, then the final results must be corrected by the difference.

Notes on Filters.—The Jena filters must be perfectly dry before use. After each use they should be freed of adhering cement by a water jet and then warmed for some time with dilute HCl. They are then washed for a time in running water and dried in an oven. Periodically they should be warmed with dilute sodium carbonate solution, washed free of carbonate, and then treated with HCl and water as before.

Chemical Analyses

The chemical analysis of cements, if taken in conjunction with the mechanical and physical tests, affords much desirable information in the selection of a good quality material; indeed, it is almost necessary that both the chemical and mechanical examinations of a cement should be made before the positive pronouncement of quality can be given, and when both have been ascertained the suitability and efficiency of a cement for any given purpose can be at once accurately determined. In recent years there has been a substantial improvement in the application of well-known processes, such as the mechanical and chemical modes of evaluation, but there has been little alteration in principles.

It is not definitely known just what part is played by each of the compounds that constitute present-day Portland cements, and chemical analyses do not explain the manner of the occurrence of these compounds. The definite aid which chemical analysis may render in determining the quality of a cement is therefore limited to ascertaining that the essential compounds are present in the proportions which experience has proved to be necessary or most desirable for the cement in question, and to detect adulteration. Neither complete nor partial chemical analysis of the constituents of hydraulic materials can therefore be ranked as infallible tests, or tests of primary importance: but chemical analysis may render real service in controlling the classification of a product concerning which there is reason to doubt the declaration of the manufacturer. Thus a slag cement can be distinguished from a Portland cement by its composition, as also may certain natural cements.

The chemical constituents of a well-made sample of Portland cement may be somewhat as under :

	Per cent.
Loss on ignition	1·22
Silica (SiO_2)	21·44
Insoluble residue	0·20
Alumina (Al_2O_3)	6·75
Oxide of iron (Fe_2O_3)	3·17
Lime (CaO)	63·44
Magnesia (MgO)	0·99
Sulphuric anhydride	1·81
Potash and soda	0·98

100·00

There is a change in composition of the materials during the burning stage which is almost inevitably in the direction of reducing the lime factor. This is caused by the impurities picked up during the calcining process, such as a slight mixture of kiln linings and ash from the fuel used in the kiln. These additions are chiefly composed of silica and alumina, and they affect and alter the theoretical composition of the cement, as calculated from the raw materials used, by slightly increasing the percentages of silica, iron, and alumina, and reducing the lime content

Effect of Fuel Ash

The effect of fuel ash on the composition of cement as shown by analysis is illustrated by the following. The ash of the coal or whatever fuel other than oil may have been used for the calcination of the raw material, being non-volatile, remains with the clinkered mass either wholly or in part according to the type of kiln used. Part of it is fused on to the outside of the pieces of cement clinker and combines with it, and part may remain as a more or less insoluble powder or clinker chiefly consisting of silicates of alumina and iron. Such ash as is not carried away by the draught in the form of dust is inseparable from the cement clinker, and is ground with it. This affects the composition of the clinker. In the types of fixed kilns adopted formerly practically all the ash was thus left. Intermittent kilns required about 8 cwt. of coke to calcine a ton of cement, and continuous shaft kilns about $4\frac{1}{2}$ cwt. If we assume coke to contain 10 per cent. of ash, this means that

0.8 cwt. of ash was left in the first case and 0.45 cwt. in the other. This ash may have the following composition,

	Per cent.
Silica	51.0
Alumina and iron oxide	34.2
Lime	12.0
Undetermined	2.8
	100.0

and will affect the analysis of the average of the mass drawn from the kiln by reducing its percentage of lime. If in the raw material mixture the percentage of carbonate of lime be 76, and there be no volatile matter present other than the carbon dioxide belonging thereto, the amount of lime in the calcined mass, if calcined by an ashless fuel, would be 63.94 per cent. If calcined in an intermittent kiln under the conditions outlined already, the amount would become 61.86 per cent., and if calcined in a continuous shaft kiln 62.77 per cent.

Silica, Lime, and Alumina

The percentages of silica, alumina, oxide of iron, and lime contained in cements may vary considerably and still constitute a good and sound article, but magnesia and sulphuric anhydride should never exceed the percentages given in the British Standard Specification (see p. 258).

Silica, lime, and alumina must be considered the essential elements of the cement, as they combine in the kiln at a clinkering temperature to form compounds having special properties in relation to the effect that water has upon them. These compounds—silicate of calcium and aluminate of calcium—as they come from the kiln, and until they are wetted to form concrete, are perfectly anhydrous; that is, they have no water chemically combined in their molecules. They are, however, capable of forming a chemical combination with water, and in that condition are known as hydrated silicate of calcium and hydrated aluminate of calcium. The peculiarity of these compounds is that when in the anhydrous condition they are more soluble in water than when in the hydrated condition, the effect being that when wetted with water the anhydrous substance is split up and a portion dissolves in the water. It then slowly combines with the water and the undissolved portion to form hydrated compounds, which, being insoluble, bind the whole mass into a solid block. As the solubility is but slight, this reaction takes place slowly, and it may be weeks or even months before it is complete. The property is known as hydraulicity, and an hydraulic substance is one that will set under water. The aim should be to produce the maximum amount of these substances in cement. On the one hand, if there is too much lime in the mixture a portion of it remains uncombined and is a source of danger to the cement, as free lime expands and crumbles on being hydrated; on the other hand, if there is too much silica and alumina in the mixture, other compounds are formed which have no hydraulicity.

Lime expands in slaking, so that an excess of lime above what will unite with the silica and alumina will cause the cement to expand. If the percentage of lime is too low, the cement contains silica and alumina in excess, tending to produce weak cement. Unsoundness in cement is also caused by uncombined or loosely-combined lime resulting from coarse grinding or irregular mixing of the raw materials or under-burning of the clinker, and this is detected by soundness tests.

Chemical analysis, therefore, if taken alone as the guide to quality, will seldom explain fully where unsoundness is concerned. Recourse must be had in this respect to the physical tests for soundness.

A Portland cement containing high percentages of lime requires high temperatures in the kiln whilst burning the raw materials. The rotary kiln has much improved the facilities for burning cement, and has resulted in a general increase in the percentage of lime content.

An increase in the quantity of silica requires a proportionate increase in the lime content, with the result that the raw materials must be burnt at a higher temperature, and the resultant cement will have a high tensile strength. Silica is generally contained in cements to an extent of 18 to 25 per cent. It is one of the most useful constituents, but must not be in insoluble form. Silica in Portland cement plays the part of an acid and combines with lime under great heat.

The oxide of iron, generally from 2 to 5 per cent., acts as a flux in the kiln and causes the silica and alumina to combine with the lime at a lower temperature than they would without its presence. At the same time the oxide of iron enters into combination, forming similar compounds to the alumina compounds, and generally speaking the compounds of iron and alumina are interchangeable; the difference is that whereas iron oxide lowers the temperature of burning and imparts the dark grey colour to cement, alumina makes for much higher burning temperature. Cements made with no iron are white.

White Portland cement is of similar character to ordinary grey Portland cement, except that iron is almost entirely absent. For many of the purposes for which white cements are used it is not the strength at early ages so much as the appearance of the finished product or structure which is of prime importance, and as this cement is hydraulic it can be used for exterior work, which was impossible with white cements and plasters produced from gypsum, such as Keene's cement.

The amount of alumina in Portland cement is generally from 3 to 10 per cent., and it is assumed to affect the initial hardening of the material. A high alumina content, for instance, makes a quick-hardening cement, and a low percentage of alumina generally suggests slow-hardening qualities. Alumina in Portland cement acts as an acid.

Magnesia is present in cements up to about 3 or 4 per cent., a limit which is considered to be harmless; indeed, some consider that magnesia replaces lime, and this theory is growing in favour, although others maintain that an excess of magnesia may lead to delayed unsoundness.

The test for insoluble residue, such as sand, clay, and inert material of any description, is useful in ascertaining the existence of any foreign matter or adulteration, as pure Portland cement should contain considerably less than 1 per cent. of such substances, which normally consist chiefly of detritus from the kiln and mill linings and uncombined fuel ash.

Analysis of Portland Cement

There is no British Standard method for the analysis of Portland cement, and chemists may vary in their estimation of its constituents. A typical working bench is shown in *Fig. 220*, and the methods usually adopted for analysing Portland cement are conducted as follows.

Silica

Weigh 1 gr. of the sample (*Fig. 221*) into a porcelain dish, swirl round with a few c.c. of hot water, add 10 c.c. of strong hydrochloric acid, see that all lumps of

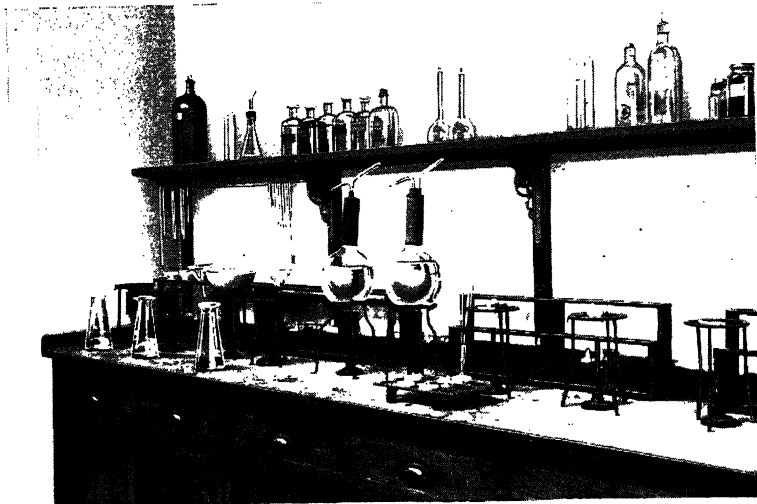


Fig. 220.—Bench in Laboratory at a Cement Works.

cement are broken up and acted upon by the acid, cover the dish with a clock glass, and evaporate to dryness on a hot plate (*Fig. 222*), carefully at first to avoid “spitting”; then bake for one hour at full heat of plate. Remove, and when dish



Fig. 221.—Weighing Samples for Analysis.

is cool enough to handle, add 25 c.c. of strong hydrochloric acid; leave for 15 minutes, warming very gently if necessary, until all red colour of the iron salts has disappeared. Dilute with water, filter off separated silica and insoluble residue, wash well, dry, burn off, muffle for 1 hour, cool and weigh.

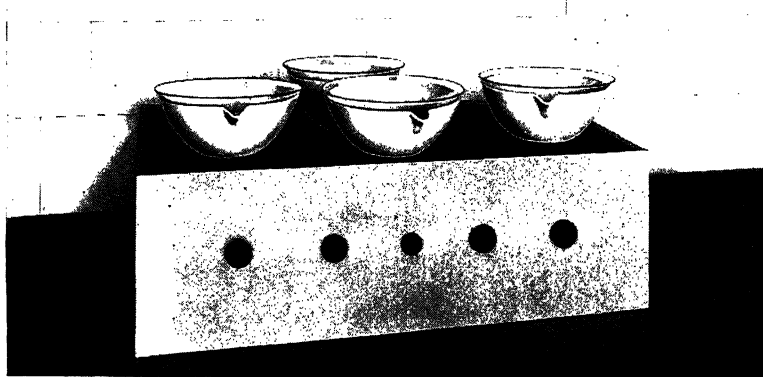


Fig. 222.—Hot Plate.

Ferric Oxide and Alumina

The solution from the silica determination, having been collected in a suitable beaker, is washed back into the porcelain dish, heated to boiling, a few c.c. of bromine water added, then 50 per cent. solution of ammonia added very slowly until the solution is neutral, then 2 c.c. in excess are added, and the mixture boiled for 2 minutes. The precipitate is filtered off, washed twice, and then washed back into the dish, dissolved in a few c.c. of hydrochloric acid, precipitated as before, and filtered, collecting the filtrate in the same beaker as before. This precipitate should be well washed and then dried, burnt off in muffle for 1 hour, cooled and weighed.

FERRIC OXIDE.—A separate portion of 1 gr. is weighed into a porcelain dish, dissolved in hydrochloric acid and water, heated to boiling, and reduced with stannous chloride. When cool, 15 c.c. of a saturated solution of mercuric chloride are added, allowed to stand for 10 to 15 minutes, and titrated with a standard solution of potassium dichromate.

LIME.—To the combined filtrates from the double precipitation of the iron and alumina add 30 c.c. of 50 per cent. solution of ammonia and bring to boiling; then add 70 c.c. of a saturated solution of ammonium oxalate, boil for 5 minutes, and allow the precipitate to settle. Decant as much of the clear solution as possible through a filter paper, keeping the precipitate in the beaker, wash two or three times by decantation. Now dissolve the precipitate in dilute hydrochloric acid and boil. Re-precipitate with ammonia and ammonium oxalate, and allow the precipitate to settle. Filter through the same filter paper, allowing the filtrate to mix with the first one. Wash the precipitate with warm water, thoroughly dry, burn off in platinum crucible, ignite gently at first until all carbon is burnt off, then strongly ignite in the muffle-furnace (*Fig. 223*) until the weight is constant. The calcium oxalate is thus reduced to oxide and weighed as such. The method of filtering a lime precipitate is shown in *Fig. 224*.

Magnesia

The filtrations from the lime are evaporated to small bulk by boiling down in a porcelain dish. When the liquid has been reduced to as small bulk as possible on the burner it is taken to complete dryness on the hot plate with the addition of 50 c.c. of strong nitric acid to destroy the ammonium salts. When cool, take

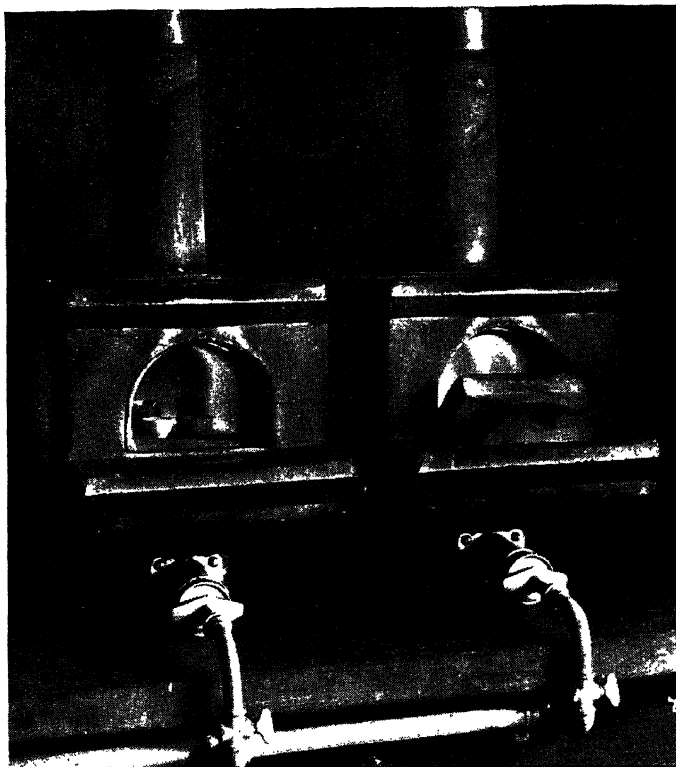


Fig. 223.—Muffle Furnace.



Fig. 224.—Filtering Lime Precipitate.

up with dilute hydrochloric acid, neutralise with ammonia, and filter off any precipitate. An excess of sodium phosphate solution is added, viz. about 5 c.c. of a saturated solution together with about 20 c.c. of strong ammonia, and the solution stirred briskly for about 5 minutes and allowed to stand over night. The precipitate is then filtered off and washed with cold dilute ammonia solution (10 per cent.). The precipitate is then dried (*Fig. 225*), ignited (first gently, afterwards in the muffle), and weighed as magnesium pyro-phosphate.



Fig. 225.—Drying Precipitate.

Sulphuric Anhydride

Weigh 1 gr. of the sample into a porcelain dish, dissolve in hydrochloric acid and water as before, boil for 5 to 10 minutes to ensure all going into solution that will filter, and wash well. The filtrate is caught in a beaker, raised to boiling, 10 c.c. of a solution of barium chloride added, and the whole boiled for a few minutes. The precipitate of barium sulphate is allowed to settle over night in a warm place, filtered, washed well with hot water, dried, ignited, and weighed.

Insoluble Residue

The insoluble portion from the above is washed back into the porcelain dish, 20 c.c. of a saturated solution of sodium carbonate added, boiled for 10 minutes, filtered, washed thoroughly with hot water, dried, ignited, and weighed.

Loss on Ignition

One gramme of the sample is weighed into a platinum capsule, placed in the front of the muffle furnace, left for 20 to 30 minutes, cooled, and weighed.

Sulphur as Sulphide

Weigh 2 gr. of the sample into a porcelain dish of suitable size, add a crystal or two of potassium chlorate, dissolve in 25 c.c. aqua regia, evaporate to dryness, heat until dehydration is complete, take up with hydrochloric acid and water, and filter off silica in usual way. In the filtrate, determine the sulphuric anhydride by precipitation with barium chloride. This will give the total sulphuric anhydride, and the sulphur present as sulphide will be given by deduction of the sulphuric anhydride determined as such in the ordinary way, and a calculation to convert sulphuric anhydride into sulphur. This method, though not strictly accurate, owing to the readily soluble ferric salts reacting with the H_2S formed and with any undecomposed sulphides tending to give high results for the sulphate content, and therefore a correspondingly low result for the sulphide present, is generally considered accurate enough for Portland cements in which the sulphide content is very small.

Potash and Soda

Weigh 5 gr. of the sample into a platinum dish, dissolve in hydrochloric acid and water, evaporate to dryness, bake, take up with acid, and filter off silica in the usual way. In the filtrate precipitate sulphuric anhydride with barium chloride, after standing in warm place for a few hours without filtering, add ammonia and ammonium carbonate in excess to precipitate alumina, ferric oxide, lime, and barium; filter off all together and wash well; redissolve the massed precipitates in a minimum quantity of hydrochloric acid, reprecipitate with ammonia and ammonium carbonate, filter, and wash well. Take combined filtrates to dryness in platinum dish; burn off ammonium salts. Take up with a few drops of water, add ammonium carbonate, precipitate, filter off, evaporate to dryness, burn off ammonium salts as before, and repeat until no precipitate is formed. Next, add ammonium carbonate, an equal volume of alcohol, allow to stand for not less than 2 hours, filter off precipitate (some lime, chiefly magnesia), evaporate filtrate to dryness, burn off ammonium salts, take up with water, filter, add 2 or 3 drops of hydrochloric acid to filtrate, evaporate to dryness in platinum dish, burn off any ammonium salts, and weigh as the mixed chlorides. Dissolve the mixed chlorides in water, add an excess of platinic chloride solution. Evaporate nearly to dryness, add 20 c.c. of 80 per cent. alcohol, and allow to stand until the sodium salts dissolve. Filter through a small filter paper and wash with 80 per cent. alcohol until washings run through perfectly colourless. Dry the filter paper and dissolve precipitate on it by washing with hot water, allowing washings to run into weighed platinum dish; evaporate off water, dry at 135 deg. C., and weigh as potassium platinic chloride. A calculation then gives the soda and potash.

Carbon Dioxide

Weigh 5 to 10 gr., according to the amount present, into a 250 c.c. round-bottomed flask and connect to the apparatus (*Fig. 226*), which is designed so that only air free from CO_2 , SO_2 , H_2S , etc., can enter from the outside atmosphere, and that only CO_2 from the cement can be absorbed in the potash bulbs; aspirate for one hour to ensure the apparatus is free from contamination by carbon dioxide from the atmosphere. Next connect the weighed potash absorption bulb and guard tube and put 20 c.c. of strong HCl in the bulb of the dropping funnel in the neck of the flask, having previously closed all taps; turn aspirator on full and open the

taps one by one from the aspirator end, seeing that the apparatus is gas-tight after opening each tap. Then very slowly open the tap in the bulb containing the acid, just sufficient to cause an evolution of gas through the potash absorption bulb at the rate of one bubble per second. When evolution of gas is complete, open full the tap controlling the acid, and adjust the aspirator to maintain the correct rate of bubbling through the potash absorption bulb; turn on water to the condenser, and apply heat to the flask; heat to boiling, and boil for 10 to 15 minutes, after which continue aspirating for one hour to ensure complete absorption of all the carbon dioxide which has been liberated from the sample. Remove the potash absorption

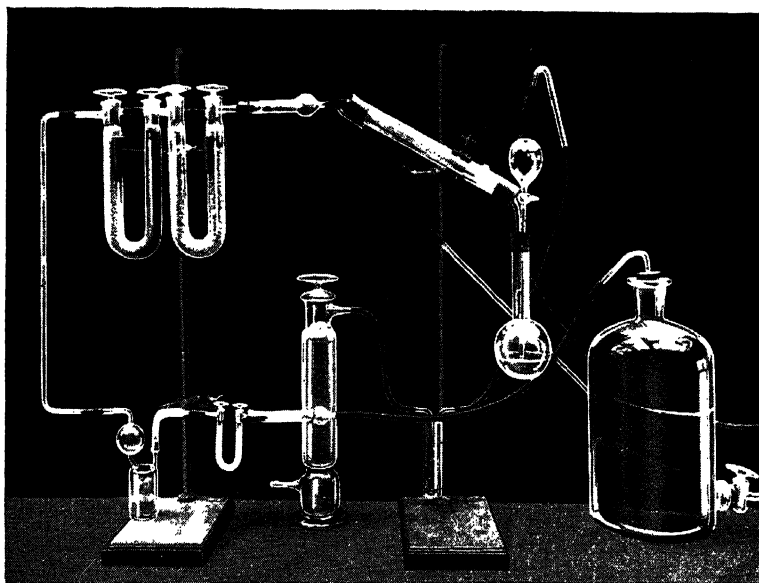


Fig. 226.—Apparatus for Determining Carbon Dioxide.

bulb and guard tube. Leave in the balance case for half an hour to get to atmospheric temperature, then weigh. Increase in weight represents the carbon dioxide.

The results calculated to percentages are then tabulated as follows:

	Per cent.
Loss on ignition (water, carbon dioxide, and other loss)	
Silica (SiO_2)	.
Insoluble	.
Ferric oxide (Fe_2O_3)	.
Alumina (Al_2O_3)	.
Lime (CaO)	.
Magnesia (MgO)	.
Sulphuric anhydride (SO_3)	.
Alkalis (potash and soda)	.

CHAPTER XXII

SETTING AND HARDENING

THE setting of cement is still imperfectly understood ; its complex constituents have not yet been completely isolated, or their individual behaviour fully ascertained. Until this detailed knowledge has been gained discussion is largely a matter of hypothesis. A great deal has been written on the subject during recent years, and it is held that the process of setting arises either from crystallisation or colloidal action, or both.

It appears to be accepted by the two main schools of thought that the adhesive and cohesive qualities of set cement arise largely from the presence of low-limed compounds, although it is not always agreed that the hydrolysis goes so far as to result in hydrous silica, because hydrate of lime would be produced concurrently with the silica and, as fairly rapid combination takes place, the two substances cannot long exist together. Thomas Edison once explained to the author that he was a keen believer in the colloid theory of setting, while Le Chatelier always opposed the theory which attributes hardening to certain colloidal properties of cement. Other authorities also hold definite and opposite views. In his work on the microscopic analysis of the constitution of Portland cement, published so long ago as 1887, Le Chatelier stated that he found the main constituents of Portland cement to consist of colourless double-refracting cubical crystals and between these a darker substance, doubly refracting but without crystalline structure. In addition he found (a) slightly yellowish crystals, opaque and showing striation ; (b) very small crystals with rather strong double-refraction ; and (c) zones of matter without influence on polarised light.

Le Chatelier also pointed out that in an endeavour to define the word " colloid," Graham (the originator of the discovery of the bodies so called) had recognised the existence of two different solutions, and that while the crystalloids are diffused when dissolving the colloids are not ; the one kind gave on evaporation crystallised bodies called crystalloids (sea-salt, sugar, etc.), while the other gave amorphous bodies (gelatinous silica, gum, etc.). Zsigmondy has shown with the aid of the ultramicroscope that the colloidal solutions were not true solutions, but merely suspensions of very finely divided insoluble matter. These suspensions are opaque, milky, or transparent, according to the fineness and abundance of the particles suspended in the liquid. When their diameter is inferior to the wave-length of light they allow the light to wend its way through, somewhat as does sound with screens of a limited size. The diameter of the true colloids approaches a millionth of a millimetre, and is always much less than a thousandth of a millimetre. Such colloidal suspensions are common to all very minute insoluble bodies ; for instance, metals such as platinum and silver when pulverised by the electric arc ; finely-crushed quartz, alumina, kaolin, and other minerals ; completely insoluble chemical precipitates as the sulphides (notably nickel sulphide) ; and iron tannate used in the manufacture of ink.

One special and important property of these very minute bodies entitles them to be classed separately, namely, the property of adsorbing the soluble bodies held in solution by the liquid with which they are wetted. This adsorption, which is a source of error in analyses, is frequent with chemical precipitates, but does not

strictly characterise finely-divided bodies, as it manifests itself also in porous bodies. From this point of view colloids and porous bodies must be classed together. This adsorptive power is a particular case of much more general properties which all very fine bodies possess. Chemically a body in the form of an impalpable powder behaves quite differently from the same body in the form of big lumps. There is a special chemistry of colloids and porous bodies. These particular properties are under the immediate influence of surface tension.

The fact has long been acknowledged that all chemical phenomena depend directly upon diverse forms of energy—heat, electricity, and work; the chemical reactions of combustibles liberate heat; the reactions of batteries generate electricity; the reactions of explosives, work.

Surface energy, which is measured by the product of the surface tension (or capillary tension) and of the free surface of a body, is generally infinitely small in magnitude when compared with other forms of energy. The gramme-molecule of water (18 gr.) may be assumed to have the form of a sphere of 3.3 cm. in diameter. In contact with its water vapour the sphere will have a surface tension of 0.08 gr. per linear centimetre. The surface of the sphere being 34 sq. cm., its surface energy will be $0.08 \times 34 = 2.72$ gr. cm., or 2.72×10^{-5} kg. m., which corresponds to 6.3×10^{-8} kg. calorie. The vaporisation of a gramme-molecule of water absorbs 10 calories, and its combination with lime liberates 10 calories. Its surface energy is therefore only equivalent to the one-hundred-millionth part of that quantity of heat, that is to say, negligible. If, instead of a single sphere, the water were divided into a vast number of little globules, each of one-millionth of 1 mm., their surfaces and consequently their total superficial energy would become 330 million times greater, and thus equivalent to 2 calories; that is to say, the surface energy would be of the order of magnitude of the quantity of heat which water evolves in its various chemical reactions. The surface energy in that case would no longer be a negligible factor.

There is no direct method of measuring the surface tension at the contact between solids in suspension and the liquid. Indirect considerations suggest that this tension may become a hundred times greater than that of water. The superficial energy will be increased in the same ratio, and its influence will become appreciable for dimensions of the order of a ten-thousandth part of a millimetre—dimensions much superior to those of chemical precipitates.

These considerations so far concern solely the grain size without reference to the greater or less solubility of the bodies in question. They do not furnish an immediate explanation of the usual insolubility of the colloids. A solid crystal ground to very fine grains will certainly have all the properties of colloids as long as it retains its fineness, but it will rapidly lose the latter as soon as it is brought in contact with a liquid capable of partially dissolving the substance. The energy of dissolution will be increased by the whole superficial energy of the crystal; an increase in the solubility of the fine crystals will result, and a supersaturated solution will be produced from which larger crystals will soon be separated. This fact has been very clearly verified for the very fine precipitation of calcium sulphate and barium sulphate. In order to make these precipitates coarser, and thus prevent them from passing through the filters, they are kept hot for several hours before filtration.

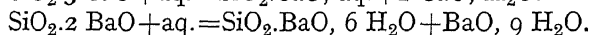
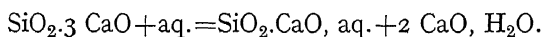
Every soluble body, even if existing in very fine division, progressively loses its colloidal properties when it is maintained in contact with a liquid in which it is somewhat soluble; its transformation will be the more rapid the greater the solubility. Only insoluble bodies can therefore preserve the extreme state of sub-division which

corresponds to the colloidal state. For the same reason bodies which are properly called colloids never show a discernible crystalline form, because the crystalline orientation supposes a certain mobility of the material within the solvent, be it liquid or gaseous.

In considering whether the products of the hardening of mortars are colloidal or not, it is interesting to take the case of plaster. When plaster has set, crystals are not discernible in the material even under the strongest magnification of the microscope. That does not prove that no crystals are formed; perhaps they are too small to be recognised. In petrographic specimen plates less than 0.02 mm. in thickness one can hardly distinguish crystals less than 0.005 mm. in diameter. Crushing the soft mass under the cover-glass does not reduce it below 0.0005 mm.—far from colloidal dimensions. When humid hydrated plaster is undisturbed crystals begin to be discernible at the end of several weeks; after several years they are sometimes visible to the naked eye. Crystals in hardening plaster are moreover visible from the beginning if the plaster is gauged with alcoholic water instead of pure water; the setting is then retarded and the crystals can better develop.

The calcium aluminates, which play an important part in the rapid hardening of cements, are hydrated at the same rate as the plaster, and they also give a whitish mass in which crystals are not discernible. If, instead of gauging the aluminate with little water, a few isolated grains of the aluminate are put into a large volume of water, the grains soon become surrounded by long crystals of hydrated aluminate, which are always easily visible under the microscope and can sometimes be seen by the unaided eye.

Calcium silicate alone causes a difficulty in these considerations; this is important, because the silicate is the essential element in the ultimate hardening of Portland cement. The microscope does not reveal hydrated calcium silicate; its crystals are certainly very minute, but numerous analogies prevent denial of their existence. The hydration is exactly the same as in the case of barium silicate:



The crystals of hydrated lime are plainly visible, like those of hydrated baryta; they may attain dimensions of several millimetres. Crystals of barium silicate can always be seen with the aid of a lens, and sometimes with the naked eye. By analogy it may be said that hydrated calcium silicate will crystallise as well; but as it is much less soluble than the barium compounds the crystals will be too minute to be discernible. It is not impossible that, initially, the dimensions of these crystals are of colloidal order, as in the moment of formation of the precipitates of barium sulphate and calcium oxalate. It has been shown, in fact, that this calcium silicate precipitate absorbs, in the moment of its formation, a certain quantity of lime which varies with the concentration of the liquid. In the course of time the dimensions of the crystals must increase considerably, as in all similar instances. The mechanical resistance, on the other hand, does not diminish with time. Consequently, the colloidal state which was possible at the beginning has nothing, it is maintained, to do with the hardening of the cement.

The theory of the hardening of cements which Le Chatelier propounded many years ago does not yet appear to have been refuted. This was as follows. The anhydrous compounds of cements, not being in chemical equilibrium when in contact with water, are more soluble than the same hydrated compounds. For this reason they give rise to the formation of a supersaturated solution from which the hydrated

compound may rapidly crystallise. The liquid, being no longer saturated, can re-dissolve more of the anhydrous compounds, and the whole mass can thus crystallise progressively by passing through a stage of transitory dissolution in a limited volume of water which at any given moment cannot maintain in solution more than a small portion of the total mass of salts present.

The crystals which are deposited from the supersaturated solutions always appear in the shape of extremely elongated needles, which have the tendency to group themselves in spherulites about certain centres of crystallisation. The entanglement of all these crystals is the only cause of the solidity of the mass. They become welded with one another when the reciprocal orientation is suitable; they adhere by simple contact, as do all solid bodies when really resting upon one another.

Finally, friction at the points of contact, even in the absence of all adhesion, suffices to produce a great strength of mechanical resistance such as is found in all tissues and fabrics whose solidity has no other origin. The finer and more elongated the crystals, the more numerous the points of contact and the greater the frictional resistance. The greater the area of contact, the more developed the adhesion. The progressive growth of the crystal dimensions by the mechanism suggested increases the part played by adhesion while diminishing that due to friction.

Turning now from these theoretical considerations of the mechanism of setting, it is proposed to discuss some of the practical considerations of more immediate importance to the manufacturer. Set cement contains hydrated lime, and if, as has been held, this hydrated lime is inert, we have the anomalous position that to secure strength in their products cement manufacturers are compelled to include the highest possible proportion of lime that is compatible with constancy of volume, while in the resultant concrete a proportion of the lime is not required. In order to attain the maximum lime content consistent with the production of sound and stable cement, manufacturers grind their raw materials finely at considerable cost and, the clinkering temperature of high-limed mixtures being high, the cost of calcination is also heavy; there is thus the apparent anomaly that the manufacturer finds his product burdened with an excess of a constituent costly to manipulate and which is ultimately found to be a diluent. The production of low-limed contents has consequently occupied the attention of many workers. The basis of their experiments has usually been blastfurnace slag, with its content of sulphur as sulphide, and such low-limed cements have been condemned on account of their sulphur content with its serious possibilities. The ordinary sources of raw material, such as chalk, limestone, clay, and shale, can, of course, be used for low-limed cement production, but the results up to the present have not been satisfactory.

It is maintained by those who have devoted much time and labour to the subject that the major constituents of Portland cement are tri-calcic silicate, di-calcic silicate, and tri-calcic aluminate. Of these constituents, tri-calcic silicate is the compound which hardens and develops the greatest strength within a reasonable time; it is the one formed with the greatest difficulty, and constitutes only about 30 to 35 per cent. of an average normal Portland cement. It may be, therefore, that the essential process for the manufacture of Portland cement is the formation of this compound, and that any improvement in the process yielding an increased percentage of tri-calcic silicate will increase the ultimate cementing value of Portland cement.

While these considerations obtain in regard to Portland cements, experience with high-alumina cements goes to show that tri-calcic silicate is not essential to the production of a material which will produce similar results.

High-alumina Cement

High-alumina cement differs materially from Portland cement in chemical composition. According to the British Standard Specification for High-Alumina Cement (1940) the total alumina content shall be not less than 32 per cent. by weight of the whole, while the ratio of the percentage by weight of alumina (Al_2O_3) to the percentage by weight of lime (CaO) shall be not less than 0.85 nor more than 1.3. It usually contains from 30 per cent. to 50 per cent. of lime, 32 per cent. to 50 per cent. of alumina, and not more than 20 per cent. to 30 per cent. of silica, iron oxide, and other constituents. It also differs in physical characteristics. In appearance it is a very dark, almost black, powder, and therefore results in a darker concrete than Portland cement.

The principal advantage of high-alumina cement is that, although it is as slow setting as normal Portland cements, yet it hardens so rapidly that in 24 hours concrete made with it is as strong as Portland cement concrete formerly was in two or three months, although, of course, there is not so much difference compared with present-day rapid-hardening Portland cement. The B.S.S. for High-Alumina Cement (1940) stipulates that the initial set of test blocks made in accordance with the Specification shall be not less than two hours nor more than six hours, and that the final set shall take place not more than two hours after the initial set.

High-alumina cements are less susceptible to low temperatures during setting owing to the more rapid generation of heat due to chemical reaction than is the case with Portland cements. This, however, is by no means an unmixed blessing, because, as mentioned earlier in connection with rapid-hardening Portland cement, in works of considerable thickness, where the heat generated is not rapidly dissipated by radiation, the temperature rise may call for careful consideration.

High-alumina cement does not increase in strength in the same way as Portland cement. At 24 hours high-alumina cement concrete has acquired most of its ultimate strength and is then very much stronger than Portland cement at the same age, but afterwards Portland cement concrete steadily increases in strength until it reaches the same ultimate strength as high-alumina cement.

Control of Setting Time

From the early days of the industry it has been customary to control the setting time of Portland cement by the addition of calcium sulphate, usually in the form of raw gypsum stone, during the grinding of the clinker. With well-burned clinker from rotary kilns an addition of up to about 4 per cent. of the raw gypsum stone may be necessary in order to produce a really slow setting cement. This, however, depends partly upon the raw materials and degree of burning and on the purity of the gypsum. It has to be borne in mind that the addition of gypsum increases the content of sulphuric anhydride (SO_3) found on analysis of the cement, and that all specifications place a limit on the amount of this constituent that may be present. In the British Standard Specification for Portland Cement this limit is 2.75 per cent. The action of the gypsum is at present only imperfectly understood and a fuller knowledge of the mechanism of the setting of cement is necessary for its proper appreciation. It is probable that with most Portland cements the useful content of SO_3 falls within very narrow limits. As illustrating this point and the abstruseness of the phenomenon of setting, it is sometimes found that an addition of gypsum sufficient to give an SO_3 content in the cement of, say, 1.2 per cent. may have no

apparent effect on setting, which remains instantaneous, whereas raising the SO_3 content to 1.3 per cent. will produce slow setting which is not further retarded to any appreciable extent by additional quantities of gypsum.

In the latter half of the nineteenth century it was common practice with users to lay cement out for "aeration" before use. This practice was primarily designed to improve the stability and constancy of volume by slaking any free lime present owing to incomplete combination in the kilns then used. The operation, however, also had an important effect upon the setting of the cement by the absorption of atmospheric moisture, and this effect has been made use of by the manufacturer, who has recourse to steam hydrating in the mills during the clinker grinding operation, "weathering" of the clinker before grinding, or watering of the hot clinker when leaving the kilns. These methods of slowing the set have been necessary where the addition of gypsum was found to be partially ineffective, but they cannot always be depended upon to give satisfactory results. Gypsum is often more effective in its burnt state as plaster of Paris than in the new state.

Quick setting is a pronounced feature of untreated rotary kiln cement, and it has to be regulated by these means to the setting times required in the marketable product. Generally speaking, after being mixed neat with water, cement should remain inert for at least half an hour, but after that time the quicker it sets the better.

The addition of gypsum is recognised by practically all standard specifications because a cement which varied in its setting time from a few minutes to some hours would prove exceedingly troublesome to the consumer, whereas, by the introduction of the gypsum while the cement is passing through the grinding machinery, a product is obtained which can be relied upon for a slow and generally uniform set. This addition of gypsum in no way interferes with the strength or quality of the cement.

The watering or hydrating of well-burnt clinker to regulate the setting of cement is of advantage, as the set generally becomes slow under this process and the finished cement can be regulated to any approximate time of set by a combination of hydration and gypsum. It is, however, quite easy to think of the setting of cement too precisely in terms of hours or minutes, and while some measure of time is necessary for classification purposes, an exaggerated value may be attached to differences of a few minutes in results recorded with neat cement paste by the customary methods of test. A broader classification in terms of the grade of cement, i.e. quick or slow, is generally sufficient. Occasionally cements which are slow-setting when freshly ground have been known to undergo conversion to quick-setting on storage, and eventually revert to slow setting again; this is probably due to an effect associated with the addition of gypsum. Gypsum is soluble and retards the setting, but when the sulphate of lime enters into combination with the calcium aluminate its restraining action is removed and the cement becomes quick-setting for a time.

"False" Set

Of recent times a phenomenon described as a "false initial set" has been occasionally observed. The pat of neat cement paste, gauged in the customary manner for test, is seen to lose its surface moisture and assume the stiff and dull appearance associated with initial setting very soon after gauging. It may even harden to an extent sufficient to prevent the testing needle entirely penetrating the pat. The cement remains in this condition for an appreciable time before the final set (which is of a normal character) is recorded. If the pat is immediately re-gauged

on the appearance of the "false initial set" it is found that it does not recur and the pat takes its initial and final set in a normal way. The phenomenon is thought to be explained by the partial dehydration of the gypsum used for slowing the set, caused by the high frictional temperature of the grinding mill. Cooling of the mill by the application of water is now practised.

Hot Cement

It is generally understood that a quick-setting cement, or a cement which has reverted to quick set, is rendered of a slower setting nature by storage, on account of the hydration of the calcium aluminate contained in it. A quick-setting material is sometimes assumed to be one which has not been stored, and is termed "hot" or "fresh." These terms are undoubtedly very misleading to the average cement user; freshly ground cement is hot, but it is not necessarily quick-setting, nor is quick-setting cement necessarily freshly ground. All cement is hot to the touch when it is freshly ground owing to the frictional heat generated during the grinding operation, but if it has been properly made and the set regulated it will not set quickly. Urgent demands sometimes make it necessary for manufacturers to deliver consignments direct from the mills to the construction job; on arrival at the site it may be hot to the touch, and some doubts have arisen whether it is advisable to use cement in this condition. Such cement can, however, be safely used at once.

Samples taken immediately the cement had left the grinding mills, at a temperature of 140 deg. C., were tested when the cement was half an hour old, and at a temperature of 122 deg. C. More water was required to produce a definite consistency when the cement was hot. The hot cement set somewhat more quickly than the cool, by reason of the accelerating effect of the warmth, but between cement at 122 deg. C. and 15 deg. C. it amounted only to half an hour in the final setting time. This difference is of little importance.

After the laboratory tests a section of concrete road was laid at a point where it was liable to receive very rough usage. The section was approximately 70 sq. ft. in area and the thickness $7\frac{1}{2}$ in. The temperature of the cement just before mixing was 115 deg. C. Traffic was allowed on the slab after two days, the concrete being kept moist in the meantime. After eleven weeks of heavy duty no cracks or signs of disintegration were visible, the surface being in excellent condition.

With sand mortars made from cement at 122 deg. C. before mixing (which became 30 deg. C. in the mix) the average tensile strength after 28 days was 420 lb. per square inch, against 510 lb. per square inch when the temperature of the cement and the mortar at the time of mixing was 15 deg. C. With concrete, on the other hand, the difference was smaller; indeed, in tests made with cement at 30 deg. C. before mixing the strength was a trifle higher than in those made at the lower temperature.

With the introduction of rapid-hardening Portland cement, confusion very often arises between quick "setting" and quick "hardening." The initial setting, final setting, and hardening are successive stages in the chemical process which commences when water is added to cement. The first stage, initial setting, is the period before the paste begins to coagulate as a result of the decomposition and regrouping of the constituents brought about by the water. It is followed by final setting, which is measured by applying pressure to the surface with a "needle" and is usually considered complete when the needle only makes a slight impression. The setting may take anything from a few minutes (quick setting) to several hours (slow setting),

according to the cement. Hardening continues uninterruptedly, however, and after the final setting time has been recorded chemical changes continue and the hardening paste gradually acquires increasing strength. This latter is the "hardening" period, and it will be clear that a rapid-hardening cement is one which acquires strength and hardens quickly. Thus two cements, one ordinary and one rapid-hardening, may take the same length of time to "set," but the latter will be much the stronger at the end of 24 or 48 hours.

Determination of Setting Time

The activity shown in the transition from a paste to a hard mass when Portland cement is mixed with water indicates whether the material is of a quick or slow-setting nature, and it is important to be able to determine into which class a cement falls. The cement user must be aware of the setting characteristics of the cement he proposes to employ in constructional work, for unexpected results may ensue from lack of this information. If a quick-setting material is unwittingly used, the setting may commence before the mixing and deposition of the concrete are completed, and if this setting action is unnoticed it may be interfered with and the material will not again set for some time. The cohesive value of the cement may then be so greatly reduced as to render the work very weak. Care must be taken to ascertain the setting time of the cement before it is to be used, and also to ensure that no more mortar is mixed than can be used before it begins to set. Concrete or mortar which has been allowed partially to set is sometimes retempered or remixed for use, but this is not to be recommended unless the remixing can be done without further additions of water, otherwise the strength of the resultant material may be considerably lowered.

Cement manufacturers usually endeavour to produce a slow-setting cement which takes at least thirty minutes to begin to set when gauged in a neat paste. Quick-setting cement which commences to set in a few minutes is only made if specially ordered. Although perhaps capable of considerable tensile resistance, and therefore of value in constructional work, yet quick-setting cement must be used with care. It is employed only for special purposes, such as in operations liable to be quickly submerged by tidal water. In all cases slow-setting cement is preferable, if circumstances will allow its use.

Two distinct stages of setting are recorded in the laboratory, viz. the commencement of the setting (called the initial set) and the end, or final, set. With the Vicat type of needle, now widely used for this test and standardised in Great Britain as well as in most foreign countries, the initial and final sets are readily observed, but the results must be interpreted somewhat broadly and are not precise to within minutes. Although the method chosen for testing the setting of cement may not give absolutely exact and precise results, it is satisfactory because one definite test has been adopted with well-defined conditions.

The method of applying a needle of a known weight and area has been adopted from the earliest times, and the British Standard Specification for Ordinary Portland and Rapid-Hardening Portland Cements requires that a needle of a type developed from that used by Vicat and illustrated in *Figs. 227 and 228* shall be used for testing the setting times. The methods for performing the test are described in the Specification as follows :

VICAT APPARATUS.—The initial and final setting times of the cement shall be determined by means of the Vicat apparatus.

For the purpose of carrying out the tests a test block shall be made as follows : The test block shall be made by filling the cement * into the Vicat mould, the mould resting upon a non-porous plate. The mould shall be completely filled, and the surface of the paste shall then be smoothed off level with the top of the mould. Clean appliances shall be used for gauging, and the temperature of the water and that of the test room at the time when the operations are being performed shall be from 58 to 64 deg. F. (14.4 to 17.8 deg. C.), subject to certain provisions for hot climates. The test block shall be kept during the whole time of the test at a temperature of 58 deg. F. to 64 deg. F. The test block shall be kept during the whole time

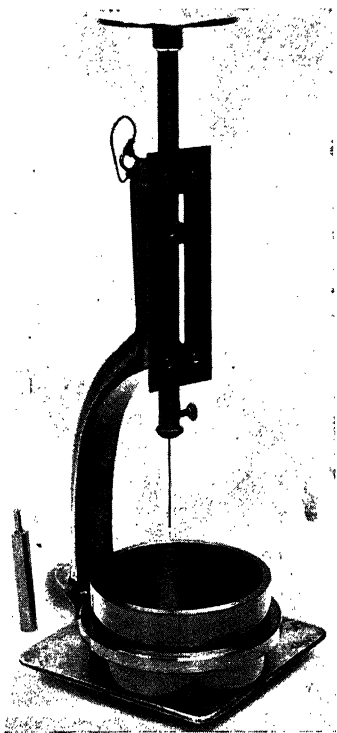


Fig. 227.—British Standard Setting Time Needle.

of test in an atmosphere of at least 90 per cent. relative humidity and away from draughts.

DETERMINATION OF INITIAL SETTING TIME.—For the determination of the initial setting time the test block confined in the mould and resting on the plate shall be placed under the rod bearing the needle ; the latter shall then be lowered gently into contact with the surface of the test block and quickly released, and allowed to sink into it. This process shall be repeated until the needle, when brought into contact with the test block and released as described, does not pierce it completely. The period elapsing between the time when the water is added to the cement and the time at which the needle ceases to pierce the test block completely shall be the initial setting time.

* Gauged as described under Tests for Normal Consistency of Cement Paste (see p. 290).

DETERMINATION OF FINAL SETTING TIME.—For the determination of the final setting time the needle of the Vicat apparatus shall be replaced by a needle with an annular attachment. The cement shall be considered as finally set when, upon applying the needle gently to the surface of the test block, the needle makes an impression thereon while the attachment fails to do so. In the event of a scum forming on the surface of the test block, the underside of the test block may be used for determining the final set.

Fig. 228 is a diagrammatic illustration of the Vicat apparatus reproduced from the British Standard Specification issued in 1940, where it is described as follows, the figures in brackets being approximate equivalents :

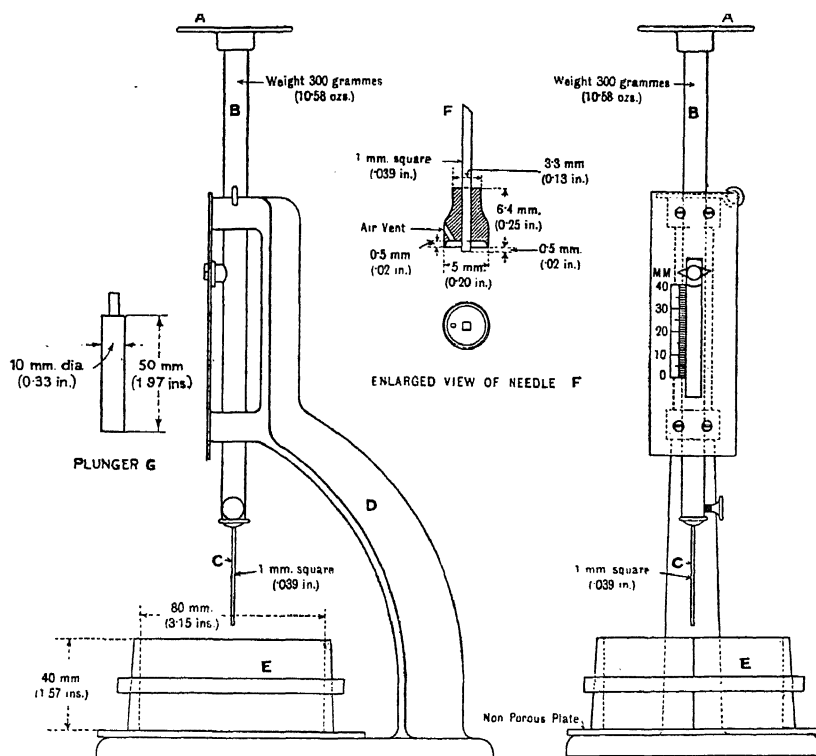


Fig. 228.—Standard Dimensions of Setting Time Needle.

The Vicat apparatus consists of a frame (D) bearing a movable rod (B) with at one end the cap (A) and at the other one of the following, which are removable: (a) The needle (C) for determining the initial setting time, (b) the needle (F) for determining the final setting time, or (c) the plunger (G) for determining the normal consistency. The needle (C) shall be 1 mm. (0.039 in.) square in section and have a flat end. The needle (F) shall be of the same shape and section as needle (C), but shall be fitted with a metal attachment hollowed out so as to leave a circular cutting edge 5 mm. (0.20 in.) in diameter, the end of the needle projecting 0.5 mm. (0.02 in.) beyond this edge. The plunger (G) shall be of polished brass 10 mm. (0.39 in.) in diameter, 50 mm. (1.97 in.) long, with a projection at the upper end for insertion into the movable rod (B), and the lower edge shall be flat. The movable rod (B) carries an indicator which moves over a graduated scale attached to the frame (D).

With all attachments, the cap and rod, with needle (C) or needle (F), or plunger (G), shall together weigh 300 grammes (10.58 oz.). The mould for the cement consists of a split ring (E) 80 mm. (3.15 in.) in diameter, 40 mm. (1.75 in.) high, which rests on a non-porous plate.

It is prescribed that normal setting ordinary and rapid-hardening Portland cements shall have an initial setting time of not less than thirty minutes and a final setting time of not more than ten hours. If a quick-setting cement is specified it must have an initial setting time of not less than five minutes and a final setting time of not more than thirty minutes.

By means of a microscope and with a magnification of about 200 it is possible to watch cement in the process of setting, and for this purpose a little cement should be dusted on to the slide and fastened down by a cover-glass, and both placed under water. It will then be noticed that the grains of cement become covered with crystals, which make their appearance sometimes in from ten to twenty minutes or sometimes in from ten to fifteen hours, according to the activity of the sample. These crystals are the result of the solution in the water of a portion of the cement, and their growth and interlocking on adjoining grains unite the whole into a solid mass and thus constitute the setting properties of cement. When once the crystals have formed they cannot be again dissolved; hence the weakness of cement which has been remixed after setting has taken place.

A rough-and-ready form of testing setting time is to press the thumb-nail on a pat of cement and note the times of resistance to pressure. Thus, a small sample of cement is made up with about 25 per cent. of pure fresh water at normal temperature and formed on a piece of glass into a circular pat of about 3 in. in diameter by about $\frac{1}{4}$ in. thick. The initial and final setting times can then be very approximately ascertained by the impressions of the nail (or preferably by a pencil point) at varying intervals.

Tests for Normal Consistency of Cement Paste

It is well known that when the same cement is tested at different times and ages, even by the same operator, different percentages of water may be required to give the same plasticity, and widely different setting results may be shown. The use of a standard quantity of water for testing all cements in preparing the pat or sample for testing has not so far been considered practicable, and the procedure laid down in the B.S.S. is as follows:

For the purpose of arriving at the normal consistency of cement paste the Vicat apparatus is used, a plunger 1 cm. in diameter being employed. The quantity of water required to produce a paste of normal consistency is 0.78 of that required to give a paste which will permit of the settlement of the Vicat plunger to a point 5 to 7 mm. from the bottom of the Vicat mould when the cement paste is tested. The time of gauging, that is, the time elapsing from the moment of adding the water to the dry cement until commencing to fill the mould, must not be less than three minutes or more than five minutes. If a quick-setting cement has been specially specified or required, the time of gauging must not be less than two minutes or more than three minutes, and the filling of the mould must be completed within five minutes. In either case the gauging must be completed before signs of setting occur.

The cement paste is filled into the mould in the same way as for the setting-time test. In filling the mould the operator's hands and the blade of the ordinary gauging trowel alone may be used, and the trowel must weigh about $7\frac{1}{2}$ oz. The

mould, after being filled, may be lightly shaken to the extent necessary for expelling the air. The test block confined in the mould and resting on the plate is placed under the rod bearing the plunger ; the latter is then lowered gently into contact with the surface of the test block, quickly released, and allowed to sink into it. The temperature of the testing room must be between 58 deg. F. and 64 deg. F.

Trial pastes should be made with varying percentages of water until the amount necessary for determining the normal consistency, as defined, is found. This amount of water is recorded and expressed as a percentage by weight of the dry cement. This procedure is an improvement on that formerly adopted for ensuring agreement between different testers, but, even if the same percentage of water is used in mixing, differences in climatic conditions will cause the results of the setting-time test to vary considerably, owing to the marked influence which temperature and energy of mixing have on setting.

Strict conditions must be observed in testing the activity of cements. One of these is referred to more particularly in the chapter bearing on the results of fine grinding. Other very important factors are the atmospheric conditions in the test room, which have a serious influence on the speed of setting—high temperature or excess of CO_2 causing more rapid action. Generally speaking, both the initial and final periods of setting are prolonged by an increase of water in mixing, and the judgment of different observers is liable to make the test somewhat erratic and variable.

Hardening

In addition to ascertaining the setting times of cements, the variableness of the final hardening of different brands of cements is an important factor to be considered. This question is discussed in Chapters XXV and XXVI, where tensile and compression tests are described.

CHAPTER XXIII

FINENESS AND SIEVING

ONE of the first observations the user makes in regard to the quality of a cement concerns its fineness, and the cement is often passed through the fingers in order to feel the size of grain. The coarse particles can thus be readily perceived, and a practised tester is in this way able to gauge approximately the fineness of grinding. The determination of the fineness has some importance, because a finely-ground cement is stronger in mortar. The apparatus used and methods adopted in the fineness tests are not very exact, but since strictly precise results are not absolutely essential they are perhaps sufficient for the purpose, although methods of separation by air and fluid are receiving increasing attention as fineness of grinding increases.

The finer grinding of cement does not always increase—in fact, it may appear to reduce—the tensile strength of neat briquettes, but the strength of a mixture of sand and cement is definitely improved by increased fineness. This explains the growing desire for finer cement. Much has been written concerning the value of finely-ground cements, but it may be advisable to explain further the results to be expected in testing, and also in using, a finely-ground material. Unless the finer cements are competently dealt with and thoroughly understood, the cement user may be prejudiced against what is undoubtedly a superior article, and in some quarters reversion to coarse grinding has been advocated owing to difficulties sometimes experienced, such as expansion and crazing. It may be noted that the leaner the concrete mix the greater is the improvement due to the use of finely-ground cement.

Requirements of the Standard Specification

The British Standard Specification for Portland Cement calls for a cement that shall be ground to comply with the following conditions of fineness :

100 gr. (or, say, 4 oz.) of cement shall be continuously sifted for a period of 15 minutes on a B.S. test sieve No. 170 with the following results :

“ Ordinary Portland cement : The residue, by weight, shall not exceed 10 per cent.

“ Rapid-hardening Portland cement : The residue, by weight, shall not exceed 5 per cent.

“ Air-set lumps in the samples may be broken down with the fingers, but nothing shall be rubbed on the sieve.

“ The sieves shall be prepared from wire-cloth complying with the requirements of Table I of the British Standard Specification for Test Sieves (B.S.S. No. 410). The wire-cloth shall be woven (not twilled) and carefully mounted on the frames without distortion. The sieving area shall be not less than 50 sq. in. (322.58 sq. cm.) and the depth of the sieves shall be not less than $2\frac{3}{4}$ in. (69.85 mm.) measured from the surface of the wire-cloth.”

The nominal dimensions and tolerances for standard sieves for testing cements are given in Table X.

TABLE X

B.S. Mesh No. (nominal meshes per linear inch).	Nominal size of aperture (side of square).		Nominal diameter of wire.			Approx. screening area. Per cent.	Tolerance on average aperture plus or minus. Per cent.
	in.	mm.	in.	mm.	Standard wire gauge.		
170	0.0035	0.089	0.0024	0.061	46	35	8

The maximum tolerances for occasional large apertures, if present, expressed as percentages of the nominal dimensions for side of aperture in either direction, shall not exceed 50 per cent.

The same test is used for high-alumina cement, but in this case the residue on the No. 170 sieve must not exceed 8 per cent. (B.S.S. for High Alumina Cement, 1940).

Effect of Fine Grinding

Fineness of grinding is very important, because the finer the cement the more intimately it can be incorporated with the aggregate used for concrete and the stronger will be the ultimate work, or, if economy is more necessary than increased strength, a leaner mix can be used. Finer cement will show an increased strength with the same proportion of sand, or equal strength with a greater proportion. Tests of neat cement, or extremely rich mortar, obscure this valuable quality, and tests on neat cement are no longer included in the British Standard Specification. On the other hand, fineness of grinding alone is not to be taken as indicating the quality of a cement. Weakly-burned cements will give a larger proportion of fine material for the same amount of grinding than those ground from a harder clinker, though the latter are usually the more valuable cements.

TABLE XI

Sample No.	Per cent. residue on B.S. Sieve No. 72.	Per cent. residue on B.S. Sieve No. 170.	Per cent. flour in flourometer.
1	Trace	4.80	57.55
2	0.10	5.00	58.45
3	0.25	7.10	54.70
4	0.10	3.30	62.35
5	0.10	3.70	60.40
6	0.05	2.80	67.50
7	0.05	3.80	61.00
8	0.15	5.00	58.15
9	Trace	3.30	58.15
10	0.10	5.20	56.50
11	Trace	0.40	76.05
12	Trace	0.25	75.10
13	Slight Trace	0.40	78.25
14	Trace	0.60	76.50
15	Trace	0.30	77.50
16	Trace	0.50	75.00

Portland cement is a mixture of coarse and fine particles (respectively known as "residue" and "flour"). The value of cement with a high proportion of "flour" is, first, that the actively cementitious property of the material is principally in the very fine particles, and, secondly, that the "residue" is practically inert, or at all events hydrates so slowly that it may be regarded as so much aggregate; that is to say, this residue is clinker which has been only partially reduced in the process of grinding, so that the gauging water attacks the surface of the particles and leaves a comparatively large inactive mass in the interior. If these particles are reduced to flour they produce a good quality cement with a high tensile resistance. The proportions of coarse and fine particles and "flour" in a number of different samples of cement are shown in Table XI.

Tensile tests made with standard mortar from fine and coarse cements show the higher results produced by the finer grinding, and this is illustrated by the typical figures in Table XII.

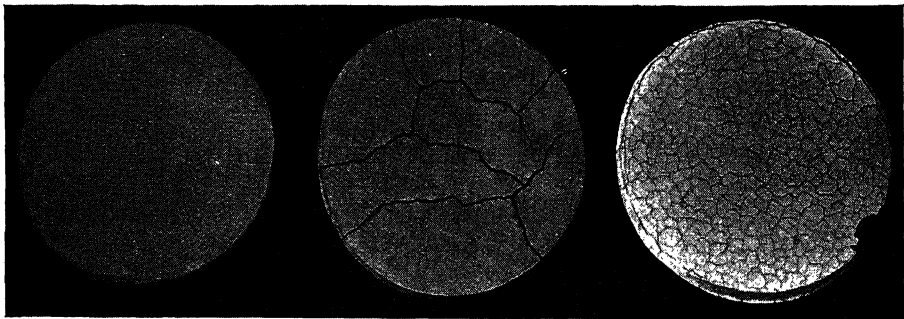
TABLE XII

TYPICAL TENSILE STRENGTHS OF BRIQUETTES MADE WITH CEMENTS OF DIFFERENT FINENESSES GROUND FROM HIGH-GRADE CLINKER. THREE PARTS STANDARD SAND, ONE PART CEMENT.

Residue on B.S. Test Sieve No. 170. (per cent.)	7 days. (lb. per sq. in.)	28 days. (lb. per sq. in.)
14	400	525
10	425	550
5	500	575
1	550	625
Trace	600	650

The advantages of finely-ground cement may be stated as follows :

Fine grinding ensures quicker hydration, as the water used in gauging acts more readily on the soluble portions of the material laid bare in greater degree by the finer grinding. It must again be mentioned, however, that cements should not



(1)

(2)

(3)

Fig. 229.—Test Pats.

be tested neat. The common tendency to develop cracks when it is made into a neat paste is increased by the larger proportion of water required to make a paste with fine cement. To illustrate this point three photographs are given of test pats (*Fig. 229*). No. 1 shows a neat cement pat which was enclosed in a damp box to set, and

was thus thoroughly sound ; No. 2 shows another pat of the same cement placed in warm air to dry, and which developed contraction cracks ; No. 3 was made with an unsound cement and boiled, and is given to show the characteristic difference between contraction and expansion cracks.

Mortar made with finely-ground cement develops considerable tensile strength in much shorter periods than a coarsely-ground product, owing to the more rapid hydration.

Cementitious Value of Fine and Coarse Grains

The character of cement residues is governed by the methods and materials used in the manufacture ; it cannot be said at what point of fineness grains of cement begin to have a cementitious value, but it is certain that the coarser particles hydrate far more slowly than the flour.

As illustrating the importance of particle size, the ground product from a rotary kiln has been divided into (a) flour ; (b) comparatively large pieces of clinker grit retained on the No. 170 sieve ; and (c) fine particles small enough to pass through the No. 170 sieve, but which are particles of hard clinker grit. It has been shown that the fine grit (c), by reason of retarded hydration, gives high expansion figures under the Le Chatelier test, whilst both the flour and the inert residue (b) give rise to only a very slight opening of the needles of the mould.

The changes under the influence of boiling water observed in the three different stages of grinding were as follows :

(a) At the time of gauging the cement the particles of flour, so-called, were hydrated more or less completely.

(b) Particles of clinker grit of comparatively large size were not hydrated, except perhaps on the surface, and acted throughout as inert material.

(c) Particles of fine grit (clinker), which were small enough to pass the 170-mesh sieve, were only partially hydrated at the time of gauging. The cement then set hard, but, under the influence of heat, when the block was boiled the hydration of these small particles continued with consequent expansion.

This would not be the case with all cements, however, and an instance of this uncertainty in the results due to the expansion of the " fine grit " particles in cement has been shown in tests of other samples of rotary kiln cement, and results obtained quite contrary to those described ; neither the difference in fineness of grinding nor the aeration of the cements appeared to make any marked difference in the expansion as shown by the Le Chatelier method of testing for soundness. It will be apparent that, although in some cements it may be found that the " fine grit " is a dangerous and expansive element with age, yet in other cements the fine grit particles have no disturbing effect at all after aeration ; so it must again be said that the function of the coarser particles in a cement is determined more by the conditions and methods of manufacture of the product than by any certain and definite result which is to be expected from all cements of whatever manufacture or process.

The proportion of flour and residue contained in a cement is a matter of considerable importance, and after the percentage of each has been ascertained in a given sample an intelligent as well as an economical use of the material should follow. The following summarises the conclusions arrived at :

(1) As a general rule, the strength of concrete made from a given cement increases with the fineness of the cement for all mixtures, consistencies, gradings of the aggregates, and ages of the concrete.

(2) Finely-ground cement is more effective in increasing the strength of poor

rather than rich mixtures, as in the latter case the increased covering power of the fine cement is not brought into play.

(3) Fine grinding is more effective in increasing the strength of concrete at early ages than at longer periods.

(4) The coarser particles of cement hydrate more slowly and the principal result of finer grinding is to hasten the early hardening of the concrete.

(5) Chemical composition is of more importance as regards quality than fineness of grinding; e.g. one brand of cement with a comparatively high residue may be as good in quality, or better, than another cement with a smaller residue.

Standard Elutriator

Since it is desirable to know the percentage of actual flour in a sample from different grinding machines used in manufacture, an apparatus (*Figs. 230-232*) has been devised for this purpose by the Associated Portland Cement Manufacturers, Ltd. The machine was designed with a view to putting the estimation of the flour content on a quantitative basis, and is known as the Standard Elutriator. The principle of this instrument is simple; a definite amount of cement is "washed" free from flour by a current of air, the non-flour residue is weighed, and the difference between the original and the final weights gives the proportion of flour blown away.

Various machines for determining the percentage of flour have been in use for some years, but the flour is not the same in proportion or particle size in any two of them. Many of these machines depend in principle upon air elutriation of the particles, but the quantity of material lifted by an air stream is governed by the size and weight of the particles and the velocity of the air. As the instruments work at different and generally unknown velocities, the percentage of flour is merely that portion of the cement that happens to be elutriated in the particular machine. For example, a sample of cement tested under standard conditions by two different flourometers contained 79.5 per cent. of flour by one machine and 71.0 per cent. by the other. The Associated Portland Cement Manufacturers, Ltd., have adopted a "standard flour" in cement as the material elutriated by air at a definite velocity of 21 ft. per minute. The average particle diameter of this standard cement flour is approximately 0.01 mm., and varies but little if elutriated at a velocity of 21 ft. per minute. The quantity of the material elutriated at this velocity is a direct measure of the fineness of the cement, and partially of its hydraulic value. Hence, a direct comparison can be made of cements of different makes.

The Standard Elutriator, which has proved efficient in use, is of the down-blast type, the air under pressure blowing into the apex of an inverted cone, thus agitating and separating the particles as well as maintaining a steady upward velocity in the elutriating tube. The apparatus (*Figs. 230, 231, and 232*) consists of a brass tube (A) 4 ft. long and 4 in. internal diameter, closed at the lower end by an air-tight machined brass cone (D) with a renewable steel apex plate. The tube is mounted in a stand carrying a manometer and a deflecting cone (B), the point of which projects $\frac{1}{4}$ in. into the mouth of the tube (A). The upper rim of this cone is formed to carry a flannel bag or filter to retain the fine dust elutriated. Air is blown into the apparatus from a small motor blower (P), through an oil trap (O) and a nozzle (J, H) which enters the elutriating tube near the bottom, and, bending downwards through the centre of the tube, terminates with a $\frac{1}{8}$ -in. diameter jet inside the bottom cone (D). The air-inlet tube is provided with a tube for attachment to the manometer, and an adjusting screw (K) for calibration purposes. Once calibrated, the

screw K is hermetically sealed and not afterwards disturbed unless recalibration becomes necessary. The rotary blower is fitted with a relief orifice controlled by a wheel valve, the adjustment of which enables a constant pressure to be maintained in the manometer. Jigs are provided to ensure that the nozzle and jet are assembled centrally in the elutriating tube and cone.

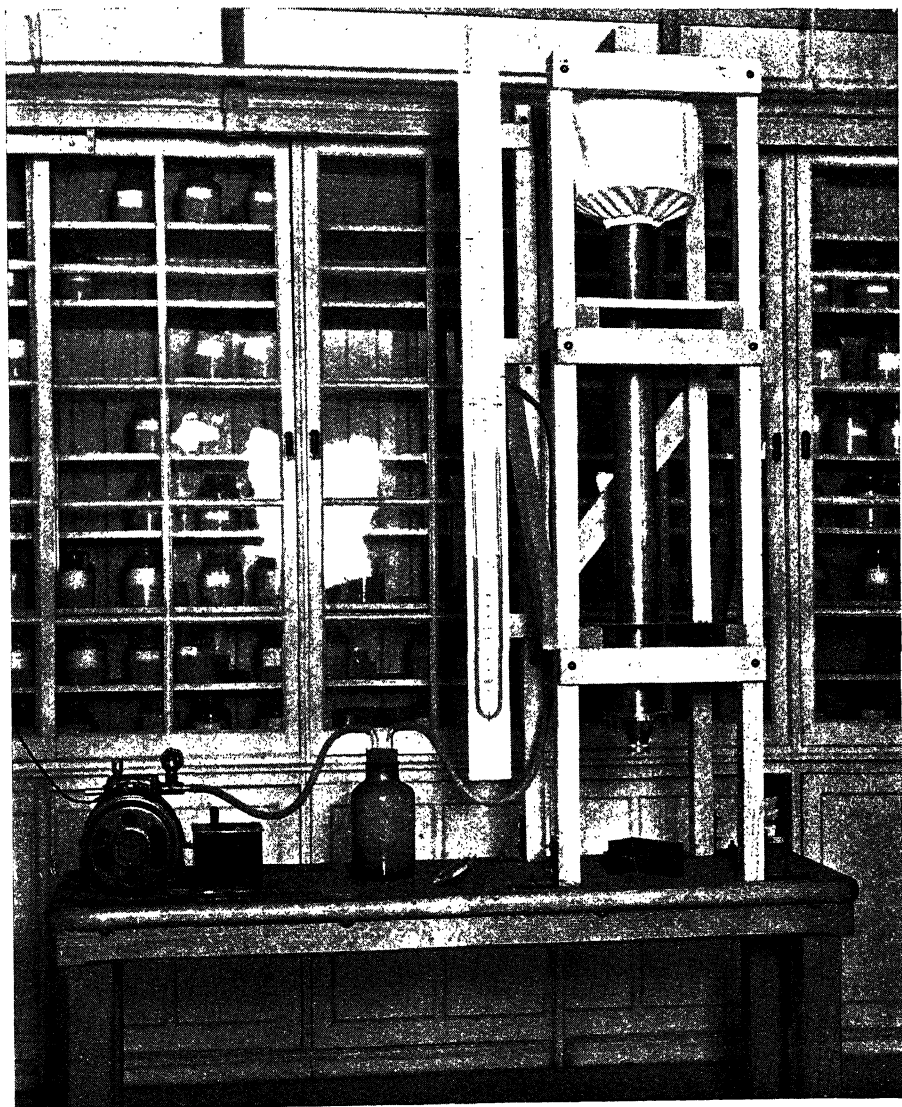


Fig. 230.—Standard Elutriator.

The test is made by placing 33.3 gr. of cement in the bottom cone, which is securely fixed to the elutriating tube by wing nuts (G). A machined recess in the base of the tube enables an air-tight fit to be made without the use of rubber or other washers. The relief valve being fully open, the motor is started and the valve gradually closed until the difference in level in the two limbs of the manometer is

41.5 in. Blowing at this pressure is continued for 25 minutes, when the motor is stopped and the cone detached from the stack. The residue in the cone, which should be dark-coloured, clean grit, free from dust, is brushed out and weighed. The difference between this weight and the 33.3 gr. taken for the experiment represents the weight of flour removed by the operation. Provided the pressure is maintained at 41.5 in. of water the air velocity in the elutriating tube remains at 21 ft. per minute, at which velocity standard flour is carried over.

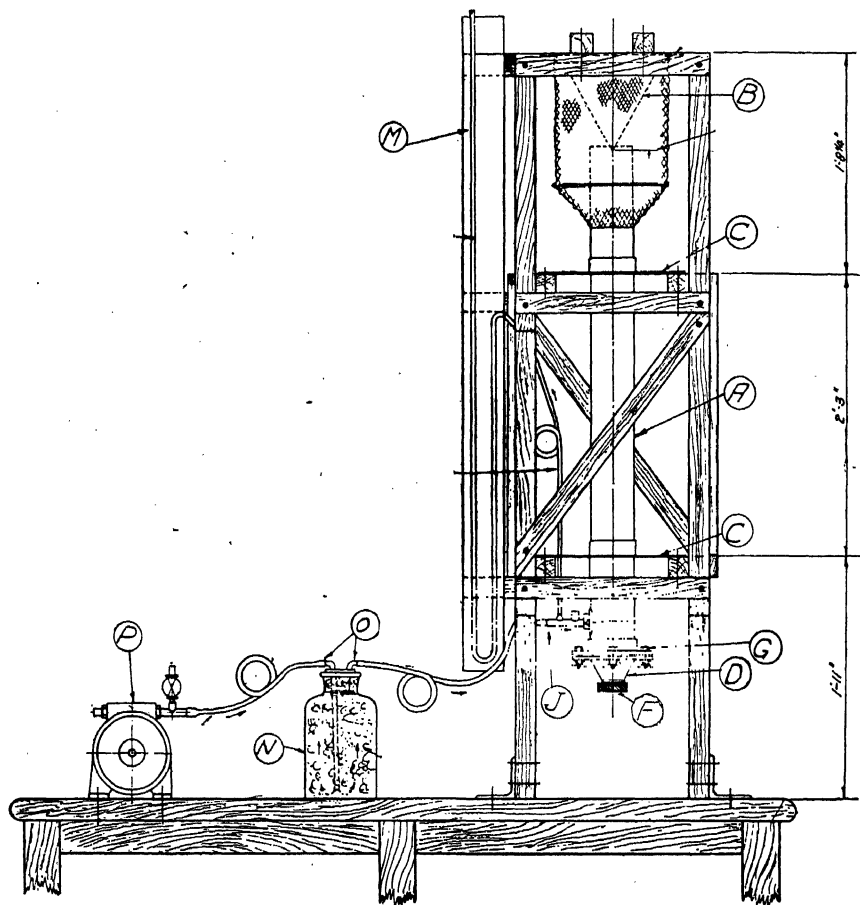


Fig. 231.—Cross Section of Standard Elutriator.

Certain precautions are necessary for accurate work. (1) The test should be made in a room with a reasonably dry atmosphere and of equable temperature. Cement flour has a great affinity for moisture, and damp air may cause the flour to stick in the tube or clog the filter. If the room is hot at one time and cold at another the accuracy of the results will be affected owing to variations in the volume of air in the elutriating tube. (2) Flour should not be left long in the flannel filter. The filter should be emptied and shaken at least daily. (3) With very fine cement containing 80 per cent. or more of standard flour it is generally advisable to tap the tube and cone occasionally during the operation to assist the air stream in agitating and separating the particles. It is also necessary to tap the tube before beginning

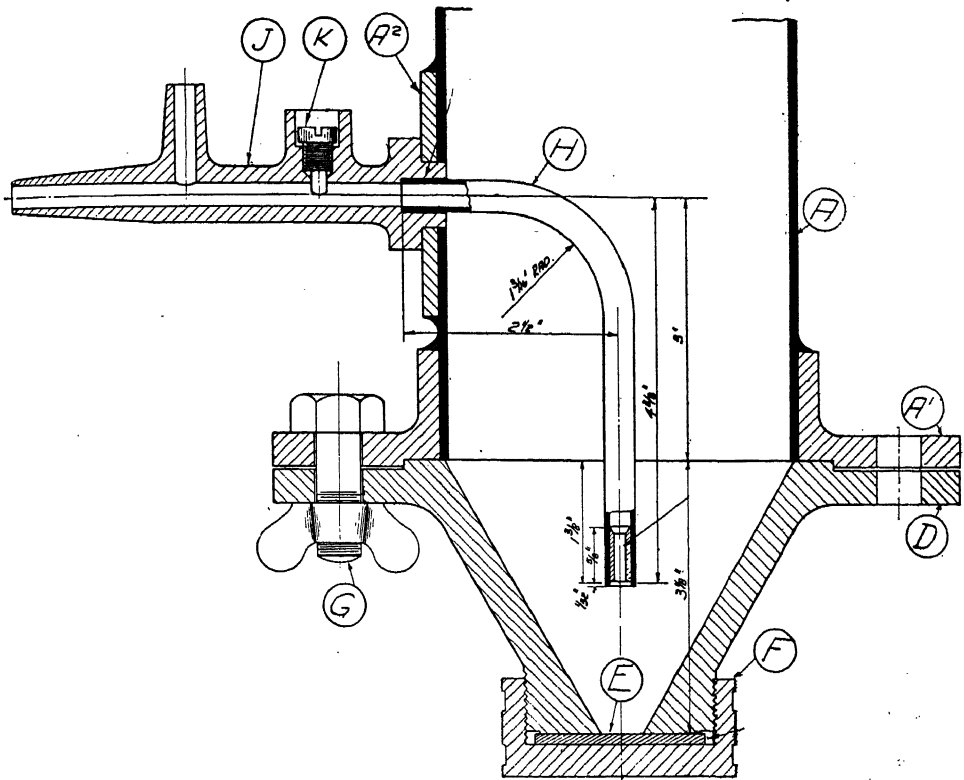


Fig. 232.—Details of Cone of Standard Elutriator.

a test to ensure that no flour from a previous test is adhering to it. (4) Care must be taken that the nozzle and jet are not damaged or displaced from the central position in the cone. With these precautions the instrument is capable of giving results agreeing within 0.5 per cent. or less in the hands of different operators.

CHAPTER XXIV

CONSTANCY OF VOLUME

ALTHOUGH, strictly speaking, there is no constancy of volume in Portland cement—since variation of moisture content, as well as heat and cold, affect its volume—yet useful results are obtained from observation of pats of cement kept in moist air or immersed in water. In sound cement the difference in volume is not noticeable without the aid of scientific apparatus, and the value of the test for constancy of volume consists in ascertaining undue expansive tendencies. The “soundness” of Portland cement is of paramount importance, and an accelerated test for soundness can be made with simple apparatus which will be comparatively free from error due to the personal equation or to local surroundings. The test for soundness obviates the necessity for long-period tensile tests as a guide to this property of cements, and the result of the test is of more value. The accelerated tests generally used are those in which a pat or block of neat cement is kept in steam or boiling water for a period.

Some rather surprising results are occasionally obtained from experiments on the soundness of cements. Contraction cracks in test pats (see *Fig. 233*), which sometimes occur during setting, are rarely a sign of bad quality. They are more generally found to be due to faulty manipulation rather than to any doubtful quality in the cement. The cracking arises from shrinkage caused by lack of humidity of the atmosphere, by rise and fall of the temperature in the test room, or by draughts of air passing over the pat while it is setting. Again, vibration of the pat while the cement is setting may cause cracking similar to a contraction crack. Contraction cracks are also found if the test pats, when moist, are left in the sun or placed on a dry porous plate; excess of water in the gauging will also cause shrinkage or contraction. The difference in the appearance of cracks thus caused and those due to unsoundness will be seen from a comparison of *Figs. 233 and 234*. Pats can best be protected from evaporation until setting has occurred by storing them in a covered damp-box or under moist cloths. The formation of cracks due to shrinkage, which may be taken by the inexperienced to be due to expansion, is avoided by these means.

The expansion of cements is generally caused by what is known as “free” or uncombined lime introduced into the product either by careless mixing or burning of the raw materials, or by the incorporation of under-burnt clinker. If cement is poorly manufactured, aeration or atmospheric slaking will, to some extent, render inert any free lime present; but a properly manufactured cement will withstand the hot or boiling tests as soon as the material is taken from the grinding mills, and no special aeration is necessary. It cannot be stated with any degree of certainty that results obtained by the boiling test—now the general test for soundness—indicate those which may be experienced in construction work, but there is no doubt that if a cement is in the slightest degree unsound this test will at once detect the weakness.

A simple test for the behaviour of cements is to make two small pats each about 3 in. in diameter by $\frac{1}{4}$ in. thick at the centre and diminishing to thin edges. The pats are gauged to a plastic paste and placed upon pieces of glass, and 24 hours afterwards one of them is immersed in cold water and the other left in a moist atmo-

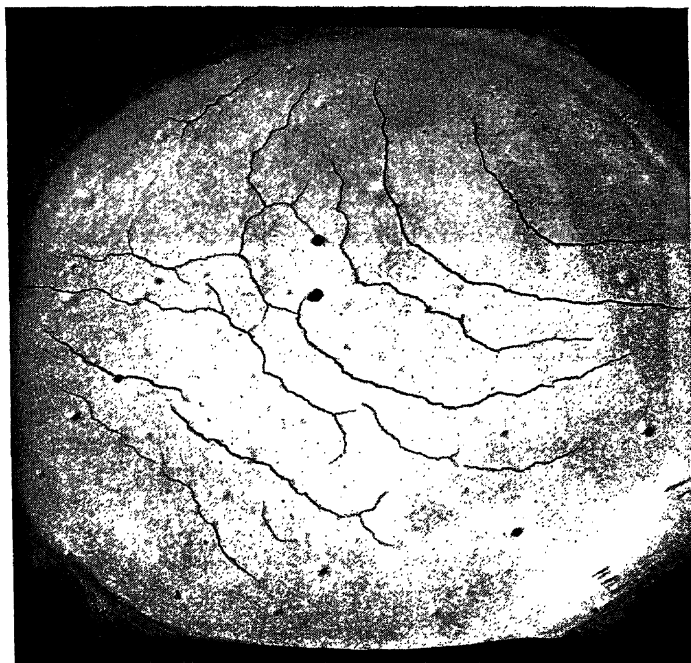


Fig. 233.—Contraction Cracks.

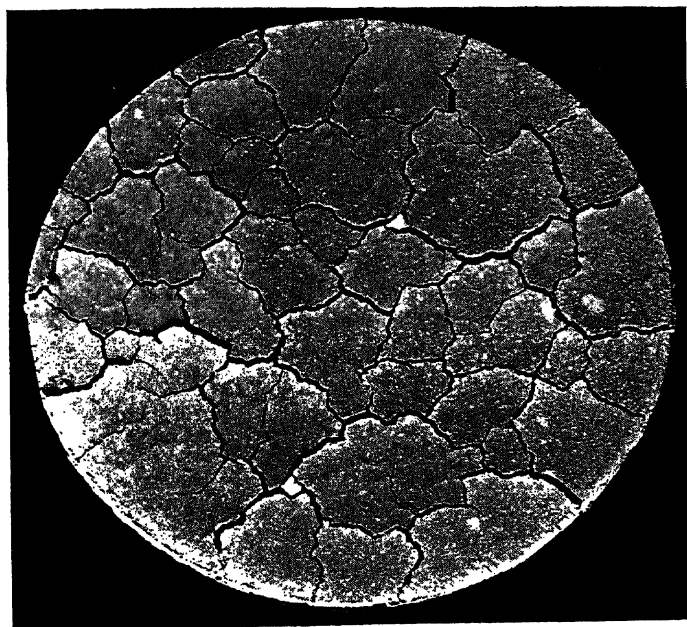


Fig. 234.—Expansion Cracks.

sphere. Both pats should be examined at regular intervals over a period of seven days, and the first indication of any disturbance or disintegration will be detected by the appearance of small cracks around the edges or extending from the centre of the pats. Other alterations of form may follow, such as lifting up at the edges or in the centre of the pat. Subject to the avoidance of contraction as explained earlier, good Portland cement will show no signs of cracking, scaling, crumbling, or warping; nor, indeed, will it suffer any deviation of form whatever under this test. Any defect in the sample will first appear in the pat under water; but since it often happens that the evidences of unsoundness take a long while to appear, this method has given way to the accelerated or hot-water tests previously mentioned. The great value of these lie in the short time which elapses before indications of defects begin to appear.

Cements which stand the accelerated tests by steam or boiling water should be used in preference to others, for although hot tests may sometimes reject suitable material they will always reject a material unsound by reason of active expansion. In the present state of knowledge it cannot be said that cement should necessarily be condemned simply for failure to pass the accelerated tests; nor can a cement be considered entirely satisfactory simply because it has passed these tests.

In the United States the terms of the Standard Specification for Portland Cement in regard to the hot test for constancy of volume are as follows: A pat of neat cement shall remain firm and hard, and show no signs of distortion, cracking, checking, or disintegration in the steam test for soundness. (Note.—Unsoundness is usually manifested by change in volume which causes distortion, cracking, crazing, or disintegration. Pats improperly made or exposed to drying may develop shrinkage cracks within the first 24 hours and are not an indication of unsoundness. The failure of the pats to remain on the glass, or the cracking of the glass to which the pats are attached, does not necessarily indicate unsoundness.) A steam apparatus which can be maintained at a temperature between 98 and 100 deg. C. is recommended. A pat from cement paste of normal consistency about 3 in. in diameter, $\frac{1}{2}$ in. thick at the centre, and tapering to a thin edge, shall be made on flat, clean glass plates and stored in moist air for 24 hours. In moulding the pat, the cement paste shall first be flattened on the glass and the pat then formed by drawing the trowel from the outer edge towards the centre, then flattening the top. The pats shall then be placed in an atmosphere of steam at a temperature between 98 and 100 deg. C. upon a suitable support 1 in. above boiling water for five hours. (Note.—It is important that the specimens be 24 hours old when placed in steam, since variations in age will produce differences in the results of the tests. Many specimens steamed when only 10 or 12 hours old give apparently satisfactory results while failure would be observed if they were not placed in steam until 24 hours old.)

The Le Chatelier Test

In the British Standard Specification for Portland Cement the soundness test specified is that known as the Le Chatelier test. The cement must not show a greater expansion than 10 mm. when first tested, but if this is exceeded it may be spread out for seven days' aeration and must not then exceed 5 mm. expansion. The apparatus (*Fig. 235*) consists of a small split cylinder of spring brass or other suitable metal 0.5 mm. thick, forming a mould 30 mm. internal diameter and 30 mm. high. On each side of the split are attached two indicators with pointed ends (A A), the distance from these ends to the centre of the cylinder being 165 mm.

In conducting the test, the mould is placed on a small piece of glass and filled with cement of normal consistency (see p. 290), care being taken to keep the edges of the mould gently together while this operation is being performed. The mould is then covered with another glass plate, a small weight is placed on this, and the mould is then immediately placed in water at a temperature of 58 deg. to 64 deg. F. and left there for 24 hours. The distance separating the indicator points is then measured, and the mould placed in water at a temperature of 58 deg. to 64 deg. F. in a suitable

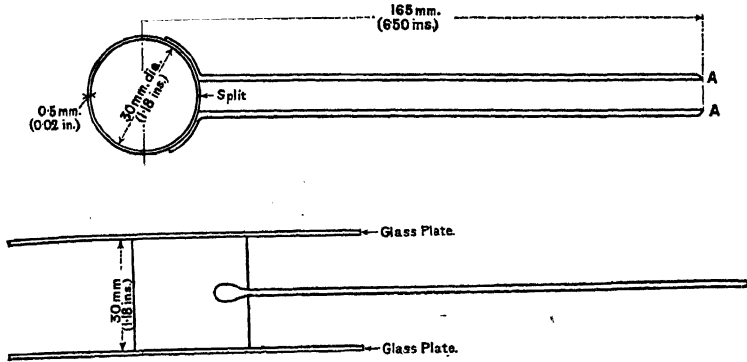


Fig. 235.—Le Chatelier Apparatus.

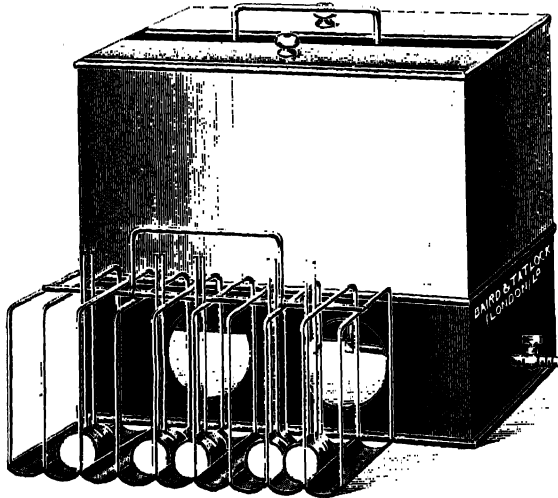


Fig. 236.—Boiling Bath for Le Chatelier Test.

receptacle, such as that shown in *Fig. 236*, which is brought to boiling point in 25 to 30 minutes and kept boiling for three hours. The mould is then removed from the water, and after cooling the distance between the points is again measured; the difference between the two measurements represents the expansion of the cement, which must not exceed 10 mm. Formerly the period of boiling was six hours, but long experience has shown that any expansion takes place within the first three hours and that the longer period serves no useful purpose. The contrast between a sound and an unsound cement under the test is illustrated in *Fig. 237*.

The test of expansion in Portland cement by the Le Chatelier method has been subjected to criticism from time to time on account of its alleged uncertainty, inaccuracy, or undue severity. This position has perhaps arisen on account of the generally accepted idea that the results of tests by the Le Chatelier method show the soundness in actual work or otherwise of the cement under test. The basis of variance between the advocates and opposers of the Le Chatelier test has been the question whether any excess over the limited increase in volume permitted necessarily indicates the unsoundness or undesirability of a cement in practice, and not solely in the test itself, which is certainly a test for showing expansion pure and simple and not necessarily "unsoundness." So the test as applied to expansion alone will here be dealt with, since many cements which are sound in practice also show considerable expansion by this test.

It has been maintained that numerous Le Chatelier tests suggest that the expansion shown on boiling is not always or necessarily due to free or loosely-combined

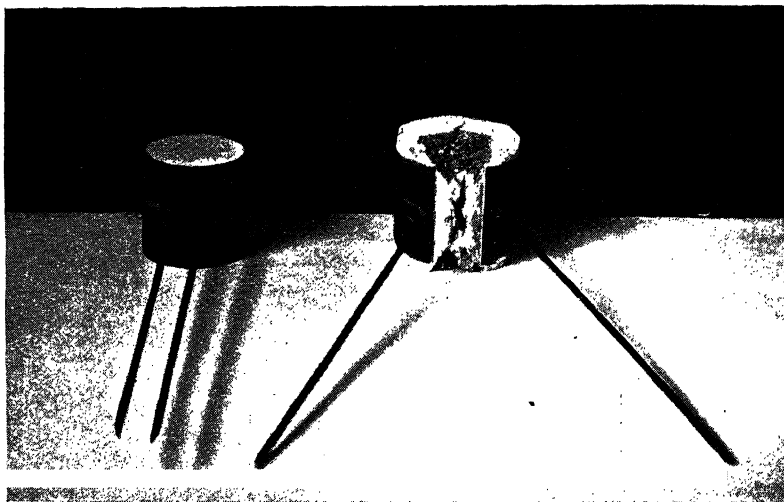


Fig. 237.—Sound and Unsound Cement in Le Chatelier Apparatus.

lime, but may be due to changes in fine particles of an intermediate size (or clinker grit) under the influence of boiling water, and explanations are given of the theory of these changes. It has been suggested, too, that cements which have been ground from clinker which has been properly burned in the rotary kiln do not improve on aeration, but on the contrary may become expansive in volume. Others, again, have advocated that the total expansion by the Le Chatelier method in both cold and boiling water should be measured, the first measurement being taken as soon as the cement has set.

In following up these conclusions, and with a view to checking the results and the theories involved, prolonged investigations were instituted by the author with the result that the finding of increased expansion with aeration cannot be generally confirmed. It is shown that the behaviour of fresh and aerated cements in the Le Chatelier test are perfectly clear and unmistakable, and at once indicate the degree of expansion—but not necessarily unsoundness—of all cements tested by this method; and many tests have shown that while aeration may not always show a

reduced expansion by the Le Chatelier method, it certainly does not show an increased expansion from the average results of a considerable number of tests. For example, in the case of what may be called a sound cement, storing in bulk was found to reduce an expansion of 2.0 mm. to one of 0.5 mm. at 21 days, and to show no expansion in 28 days. The cement when spread out reduced in expansion to 1 mm. in three days, and no expansion was shown in tests from seven days to 28 days (Table XIII).

TABLE XIII.

INFLUENCE OF AERATION ON EXPANSION.

	Fresh.	3 days' aeration.	7 days' aeration.	14 days' aeration.	21 days' aeration.	28 days' aeration.
Expansion	mm.	mm.	mm.	mm.	mm.	mm.
Cement in bulk	2.0	1.5	1.0	1.0	0.5	nil
Cement spread out 1 in. thick	2.0	1.0	nil	nil	nil	nil

To ascertain whether the same results may be expected from a similar treatment of other cements, numerous additional tests have been carried out, and the aeration of other cements gives somewhat the same results by the Le Chatelier test as shown. Exceptions to this rule are very rare.

In considering the results of numerous tests, it cannot by any means be admitted that Portland cement shows more expansion by the Le Chatelier test after a period allowed for aeration than it does when fresh. As regards the question whether an underburned or well-burned clinker shows a greater or less expansion by the Le Chatelier test, the general experience is rather in favour of the reduction of expansion by harder burning.

Now, to come to the expansion under the Le Chatelier test which results from the division of cements into varying grades of fineness, such as (a) flour, (b) clinker grit, and (c) fine sieve residue, we have three definite degrees of grinding which it is always interesting and instructive to make use of when examining cements for expansion by this method. The amount of residue left on the standard 170-mesh sieve in sifting a cement by the standard method of testing for fineness will not exceed 10 per cent. of the quantity of cement tested. From the cement passing through the 170-mesh sieve, the percentage of fine clinker grit may be collected by a flourometer, which under a steady pressure of air separates the flour from the fine grit, and the percentage content of the latter can be accurately ascertained by weighing.

The percentages of fine grit and flour vary according to the degree and process of grinding. A series of tests on two brands of cement showed that: (1) The two cements, showing respectively 2 mm. and 3.5 mm. expansion when fresh, were reduced in expansion after each successive period of seven days' aeration up to 35 and 28 days respectively, when the original expansion was again shown; but at 42 days in both cases this was reduced to 1 mm. and 1.5 mm. (2) The expansion of the residue retained on the 170-mesh sieve with both samples was 25 mm. and 24 mm. when fresh and 24 mm. and 23 mm. after 35 days. (3) The expansion of the fine cement passing through the 170-mesh sieve was reduced upon aeration from 4.5 mm. and 2.75 mm. respectively to 3 mm. and 1 mm. at 35 days. (4) The expansion of the flour in one cement was reduced from 2.25 mm. when fresh to 2 mm. after 35 days, and in the other cement the flour expansion varied from 1 mm. when fresh to 2 mm. after 35 days' aeration. (5) The expansion of the fine grit was also

reduced upon aeration from 39 mm. and 21 mm. when fresh to 36 mm. and 7 mm. respectively at the end of 35 days. Thus the degree of expansion is greatest in the coarser residues and least in the finished cement and flour. It seems from these results that the presence of the flour, the preponderating element in the finished cement, to a very large extent prevents serious expansion due to the grit in the combined sample as compared with the expansion measured when the grit alone is tested. The individual Le Chatelier test results of the component parts of Portland cement are interesting, therefore, only from the point of view of research.

TABLE XIV

LE CHATELIER EXPANSION TESTS.

(Sample of cement divided into five parts and aerated ; tests made every three days.)

Period of aeration.	Sample No. 1.	Sample No. 2.	Sample No. 3.	Sample No. 4.	Sample No. 5.
Expansion	mm.	mm.	mm.	mm.	mm.
As ground	3.0	2.0	2.5	4.5	5.0
3 days	1.5	2.0	2.0	2.0	1.5
6 "	2.5	2.5	2.0	3.0	2.0
9 "	2.5	2.5	1.5	2.0	2.0
12 "	2.0	1.5	2.0	2.0	0.5
15 "	1.5	1.5	3.5	2.0	2.5
18 "	2.0	1.0	1.0	1.0	1.0
21 "	1.5	3.0	2.0	2.0	2.0
24 "	1.5	1.5	1.0	2.0	1.0

Some variations occur from time to time in the results of tests by the Le Chatelier method as carried out by the same operator on the same cement, as is shown by the above schedule of the expansion in millimetres of a sample of cement divided into five sections and each sectional sample made up and tested at the same time but after varying periods of aeration. These variations, however, do not take the cement out of the class of a "sound" cement into that of an "unsound" one. Numerous investigations clearly show the variations of the Le Chatelier test with ordinary samples of cement and its discrepancies or idiosyncrasies. The result of each and every experiment is affected by (a) The nature of the raw materials ; (b) the process and plant used in the reduction and mixing of the raw materials ; (c) the chemical evaluation of the raw material mixture ; (d) the method of burning the mixture, the plant employed, and the fuel consumed ; (e) the degree of final grinding of the clinker, and the plant employed ; (f) the period of storing and aeration of the cement ; (g) the personal equation in carrying out the test, the percentage of water employed, temperature, etc. All these points, with others, are of importance in calculating the value of the results of the Le Chatelier expansion test. As far as can be seen there can be no disputing this value, but whether the practical soundness of a cement is to be definitely gauged by these expansion results or not is a debatable point, and this doubtless is more the bone of contention—although not so clearly put forward by objectors—than the utility of the test itself.

It has been urged, on the one hand, that perfectly sound and satisfactory cements, which will make excellent concrete and will well withstand the test of age, may sometimes expand more than the 10 mm. allowed as the limit by the British Standard Specification ; and, on the other hand, that many cements, which show little expansion by the Le Chatelier test, are inherently unsound. This in the main may be regarded as the argument supporting the contention that this test

is purely an expansion and not a soundness test. There is, however, no difficulty in producing a material which will come within the limits of expansion allowed by the British Standard Specification.

This method puts the testing of the expansion (although not necessarily the soundness) of cements upon a distinct quantitative basis—an eminently desirable step. It gives results readily calculated, clearly comparable, and at once declaring the cements most free from expansion, even if not the soundest; so long as the consumer desires to use a product possessing less expansive tendency than another, with other qualities equal, there is a distinct advantage to be obtained from its use.

The “ Cold Plunge ” Test

Soundness tests in some Portland cement specifications include the requirement that the cement shall pass the “ cold plunge ” or immediate immersion test, in terms of a clause such as the following: “ Pats on glass shall show no sign of contraction, expansion, or disintegration whether (1) after being kept in a humid chamber or in water for twenty-four hours they are placed in cold water which is then brought rapidly to boiling point and kept thereat for twelve hours, or (2) they are plunged in cold water shortly after being gauged and kept there for any length of time, or (3) they are kept entirely in moist air. The ‘ plunge ’ pats, in addition to not being cracked, warped, etc., must have a firm and permanent adherence to the glass.”

“ Unsoundness ” in the cold plunge test is sometimes looked for in the cracking of the surface of a pat which has been placed under water immediately after gauging, but more particularly in the distortion of the pat, which at times leaves the glass at the edges. This test is demanded only in rare instances and is less used to-day than formerly, and it is a test which many otherwise perfectly sound cements fail to pass. The scientific reason for so many cements showing surface cracking under this test is difficult to explain, except that it may be due to the action of water upon the scum or surface of the cement as it is setting. With slow-setting cements the cause of this surface cracking in the pats is probably due to mechanical action dependent upon the operator or the methods of carrying out the test. It cannot be definitely said that the test shows a defect in the cement, but it is certain that surface cracking is more often caused by the manipulation of the test than by any action of the cement under water. Indeed, from an experience of the vagaries of this test the defects shown by it appear to centre themselves in conditions quite outside soundness.

It has been assumed that cement containing gypsum will fail to pass the cold plunge test, but this is not so. Such an explanation has probably been put forward from time to time to explain the idiosyncrasies of the test, but it is better to admit the necessity for an inquiry than to base an explanation upon guesswork. Cements containing as much as 3 per cent. of gypsum will pass the cold plunge test, while cements which do not contain gypsum will show “ skin ” cracking and will lift off the glass. It is true that cements containing gypsum sometimes fail in this test, due perhaps to their slow-setting nature, and also because of the fine particles of gypsum and cement brought to the surface by trowelling and shaking the pat whilst it is in preparation, but from many experiments it seems more reasonable to conclude that the treatment of the pat has more to do with the cracking under the cold plunge test than has the presence of gypsum, although this does not apply to the buckling of the pat.

It has also been observed that the temperature of the water into which the cement pat is plunged is sometimes the cause of surface cracking by this test. For instance, a number of pats immersed in water at a temperature of 66 deg. F. will be found to be sound by the cold plunge test, while the same cement made into pats will lift and crack on the surface if put into water at a temperature of 45 deg. to 50 deg. F. ; it has also been noticed that in the case of two pats of the same cement, prepared in exactly the same way, if one is put under fresh water and the other under the older and alkaline water contained in the usual briquette tray, the latter pat will remain sound while the former is unsound.

Further, the soundness or unsoundness of a pat under this test is controlled to a large extent by the time elapsing between the finishing of the preparation of the pat and the time it is plunged under water. One pat, put immediately under water as gauged, will show surface cracking, while the other pat, if allowed before immersion to get a dull surface after fifteen to twenty minutes in the atmosphere (a condition showing that the initial set is likely to take place within the next fifteen minutes), may remain perfectly sound when immersed in water. On the other hand, exactly the reverse may happen.

The pats may also be affected by vibration of the water in which they are immersed. For instance, if the tank of water remains perfectly still a sound pat will often result, whilst another pat of the same cement placed in a tank where briquettes or other pats are being taken from or put into the water whilst the cold plunge test-piece is setting will show disintegration of the surface. Sometimes, again, if a prepared sample of cement be made into two pats, and one of them be shaken down and the surface trowelled, this one will crack in the cold plunge test, while the other sample of the same cement, made into a pat by merely cutting into shape with a trowel, and not trowelled on the face, will be perfectly sound under the cold plunge test. This result of trowelling is seen in a more aggravated form in some cements either as briquettes or pats. In such cases it is noticed that the skin or scum on the surface will separate if there has been much trowelling, while if there has been no trowelling the surface will remain perfectly sound. This again is clearly distinguishable from the cold plunge test crack, and if a scientific explanation were wanted the defect might be attributed to the action of sulphur compounds from the added gypsum which exists in greater quantity in the skin than in the body of the cement pat. This the author has demonstrated by experiment with successive small additions of gypsum to different cements, when it was found that ultimately in the majority of cases a time was reached when the skin of a shaken or trowelled pat or briquette would part from the body when placed in water after setting.

In observing the cold plunge pat test, therefore, regard should be paid to the results from the trowelling of the surface of the pats, for a distinction can always be made between cracking caused by over-trowelling and cracking caused in other ways. Sometimes with a freshly-made well-trowelled pat the skin will be denser, and water will find its way through this skin while the cement test-piece is setting and cause it slightly to lift and thus separate from the body of the pat in which the movement caused by infiltrating water would be much smaller. From other observations it appears that the difference between the cracks observed on untrowelled pats under the cold plunge test and those on pats which have been over-trowelled is that in the former a somewhat general but slight surface disturbance takes place resulting in fine cracks on the surface of the pats, but with the over-trowelled pats a thin skin is seen on the top of the pat and this alone disintegrates whilst the pat itself remains sound and hard.

In summarising the author's experience of this test, it would appear that as a broad general rule only slow-setting cements are affected by the cold plunge test, and this without the quality of the cement being called into account. It is clear, however, that under this test defects might be separately or collectively occasioned by (a) The result of the fineness of grinding of the raw material, and either high or low lime content ; (b) the degree of burning ; (c) the percentage of gypsum ; (d) over-trowelling of the test pat ; (e) the difference between the temperature of the cement when tested and of the water when the pat is "plunged" ; (f) the period of aeration and temperature of the cement after grinding ; (g) the method and treatment of the pats before and after "plunging."

An examination of the causes of surface cracking in the cold plunge tests shows that, from the results of a considerable number of tests, the cause may be accounted for in one or other of the defects already noticed or by a combination of them. These are some of the points which throw doubts upon the practical utility of the cold plunge test, and the results go to prove that the test is even more subject to extraneous conditions than most other cement tests. It must therefore be held that, although a pat may crack and flake on the surface under this test, it does not by any means follow that the cement is unsound, as there is a doubt as to whether the handling of the cement or the cement itself, apart from the possibility of the defect being calculable or not, is the cause of the peculiarity. The value and results of the test are equally unimportant so far as experience in practice is concerned.

It may be said that an explanation of the behaviour of cements by this test is that the surface contents of the pat differ in composition and constitution from the bulk contents (an experience not found in the practical uses of cement), and that whether a cement contains gypsum or not has little bearing upon the results by this test. A point in regard to the opinion sometimes expressed that faulty results by the cold plunge test essentially show a faulty cement is that when the test is carried out with a small amount of sand or other admixture the defect shown in the neat cement does not occur. Neat tests for tensile strength are hopelessly condemned as not representing the true qualities of the product, and they do not reflect experience in practice ; and so in the cold plunge test the neat cement results are a doubtful indication of the quality of the product.

Faija Soundness Test

A well-known test for soundness of cement is that called the Faija test. It consists in subjecting a freshly-gauged pat of cement to a moist heat of 200 deg. F. for six or seven hours, or until thoroughly set, and then immersing it in warm water at a temperature of 115 to 120 deg. F. for the remainder of the 24 hours. This accelerated test is based on the principle that moist heat accelerates the setting of cement, and that if it is judiciously applied the age of several days may be artificially given to a cement in a few hours. A sound cement acquires great hardness in a short time when treated in this way, but an unsound one, or one that would under ordinary conditions "blow" when used, is caused to develop this latter characteristic in a few hours ; hence by this test a definite opinion may be formed whether or not a cement is a safe one to use, independently of its tensile strength, which may or may not be equal to that required.

The apparatus consists of a covered vessel (*Fig. 238*) in which water is maintained at an even temperature of from 115 deg. to 120 deg. F. ; the space above the water is therefore filled with rising vapour and is at a temperature of about 100 deg.

Immediately the pat is gauged it is placed on the rack in the upper part of the vessel, and in five or six hours it may be placed in the warm water and left therein for eighteen or nineteen hours. If at the end of 24 hours the pat is still fast to the glass, or shows no sign of "blowing," the cement may be considered sound; should any signs of blowing appear the cement is spread out in a thin layer to aerate for a day or two and a second pat made and treated in the same manner.

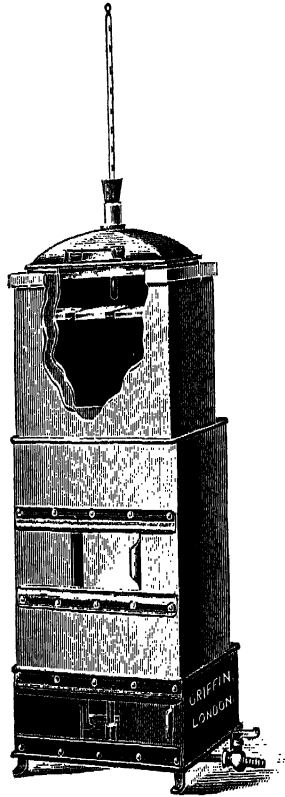


Fig. 238.—Faija Hot Bath.

Another and perhaps readier test for soundness is as follows: Prepare sample pats of cement in the ordinary way, and after 24 hours in moist air place them in a receptacle of cold water, which should then be heated gradually to boiling point and allowed to boil for three hours. If the pats are sound the cement will be thoroughly satisfactory in constructional work in so far as freedom from expansion is concerned. This is, of all accelerated tests for soundness, the simplest and most convenient for the user to apply.

CHAPTER XXV

TENSILE STRENGTH TESTS

THE strength of Portland cement may be ascertained in pure compression or tension, or a transverse test may be made, in which case shearing stresses will also be taken into account. In actual work the strain to which cement concrete is subjected may be purely tensile or purely compressive, but is more often a transverse strain. Transverse tests are, however, rarely made, the most usual strength tests for cement being tensile and compressive. When tests are required of concrete they usually take the form of compression tests. The laboratory tensile strength test as a check upon the quality of cement may be easily applied by simple and familiar apparatus. It is, however, necessary to keep in mind a distinction between laboratory tests designed as a check upon the quality of cement and tests designed to check the quality of constructional concrete.

The tensile test determines the maximum stress which, under given conditions, a cement-and-standard-sand mortar will stand before rupture. If several specimens are made separately, and all the standard conditions have been carefully observed for each of them, and yet varying results are obtained, the highest result obtained will be nearest to the correct one. Given accurate weighing of the materials, the highest result could only be too high if sufficient mortar for more than one briquette were gauged at a time and the cement unevenly distributed. Averaging the results is a practice regularly resorted to, but it is not a strictly logical procedure, as under the conditions indicated the variations obtained are due to the human factor and not to the cement. In respect of the uncertainties due to the personal characteristics of the tester and to the influence of local conditions, the tensile test contains possibilities of variations greater than any other British Standard test. The most scrupulous care must be observed in manipulation, and the tester must possess considerable knowledge and experience of such work before reliance can be placed upon his results.

A carefully made cement-and-standard-sand mortar will sustain high tensile stresses before fracture, and if the cement withstands the standard accelerated test for soundness then the high strength may certainly be looked upon as an advantage. It used to be thought that high tensile strength at an early age might be a disadvantage as indicating ultimate disintegration, but since a number of tests are in vogue for discovering expansive tendencies in cement one can readily prove the soundness of the material.

With increased knowledge of the properties of finely-ground cement it is not surprising that the tensile test of neat cement is disappearing, and that an admixture of sand should be almost universally employed in estimating the value of the sample. In the neat tensile test the full value of the cement as a concreting material, or as a cementing medium, is never demonstrated, and an inferior cement may in a neat test give tensile strength results equal or even superior to those obtained from a better cement. On the other hand, any difference between the constructive values of cements will be most noticeable in a test carried out with a mixture of aggregate and cement, and generally speaking the more aggregate used the more noticeable will be the difference. The value of sand-cement tensile tests in place of neat tests will be more appreciated if it is remembered that cement is rarely, if ever, used in a neat state.

Differences in Test Results

The experience of those with much experience in testing cements seems to show that different cements have their own distinct peculiarities which require to be understood. The strength recorded depends so largely upon details of testing that variations in manipulation, and other factors, make an appreciable difference in the results.

The following summary includes most of the common causes of divergent results in the tensile test :

(1) CEMENT.—Whether the cement is fresh or has been aerated ; if the latter, the extent thereof.

(2) GAUGING.—The amount, quality, character, and temperature of water used in gauging. The temperature of the room. Whether hand or machine mixed. Whether mixing is done on a porous or non-porous material. Quality of the sand used. Accuracy in weighing materials.

(3) PREPARATION OF BRIQUETTES.—Whether a skilled operator has been employed. The material of which the mould is composed. The shape of the mould, and the method of filling it. Whether the mould is shaken, tapped, rammed, or pressed to make the briquettes of various densities. Whether the briquettes are kept damp during setting, and whether kept in air or in water during the maturing period. Whether the briquettes are made separately or in batches and by the same operator on the same day and under the same conditions. Temperature of the air and water during gauging, setting, and storage. Condition of storage water.

(4) TESTING.—Temperature of the testing room. Length of time the briquettes have been out of water before testing. Area of the breaking section and shape of the cross-section at the point of fracture. Nature of the stress, and whether suddenly or gradually applied. The form of clips in the testing machine for holding the briquettes. Direction of the strain as regards the breaking sections of the briquettes, and the prevention of cross strains. Unequal bearing of the clips on the briquettes.

The percentage of water used in the gauging of 3 : 1 mortar briquettes is generally from 8 to 8½ per cent. of the total weight of sand and cement, according to the age, fineness, and activity of the cement ; a definite proportion of water is laid down in the British and some other standard specifications. The best results are obtained with a moderate quantity of water, and a stiff plastic mix usually gives greater uniformity ; if a very wet mix is used it is difficult to keep it homogeneous and uniformly compact in the mould. Vibrating machines or control of the pressure exerted in filling the mould is sometimes resorted to in an endeavour to control this difficulty with wet mixes, and a machine for the latter purpose is illustrated (*Fig. 239*). This is a spring balance with electrical contacts so adjusted that while the operator is exerting the desired pressure (usually from 15 lb. to 20 lb.) a white light is shown in the left-hand dial, but if 20 lb. is exceeded then a red light is shown in the right-hand dial.

The water for gauging must be clean and fresh and of a temperature of 58 deg. to 64 deg. F. Particular care must be taken that the mixing is carried out upon a non-absorbent substance, such as slate, marble, or thick glass. An iron plate may be used except where its effect on white or coloured cements may be undesirable.

The accurate testing of cements for tensile strength is not a simple process. Some experience is necessary before the materials can be manipulated so as to obtain even approximately accurate results. Tests carried out by inexperienced, though intelligent and careful, persons are usually very contradictory and inaccurate,

and no amount of experience can totally eliminate the variations introduced by the personal equation of the operator. Machines such as those illustrated in *Figs. 240* and *241* are used in some countries to avoid these variations, and so far as tests by inexperienced or partially experienced persons are concerned they help to ensure

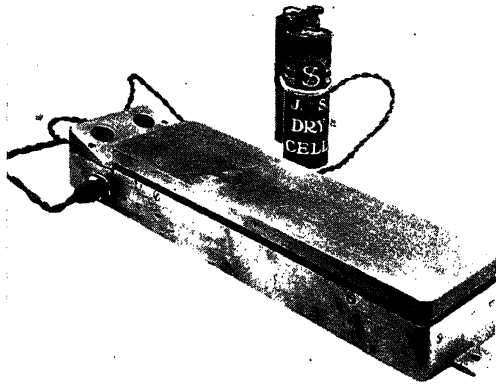


Fig. 239.—Pressure-control Apparatus.

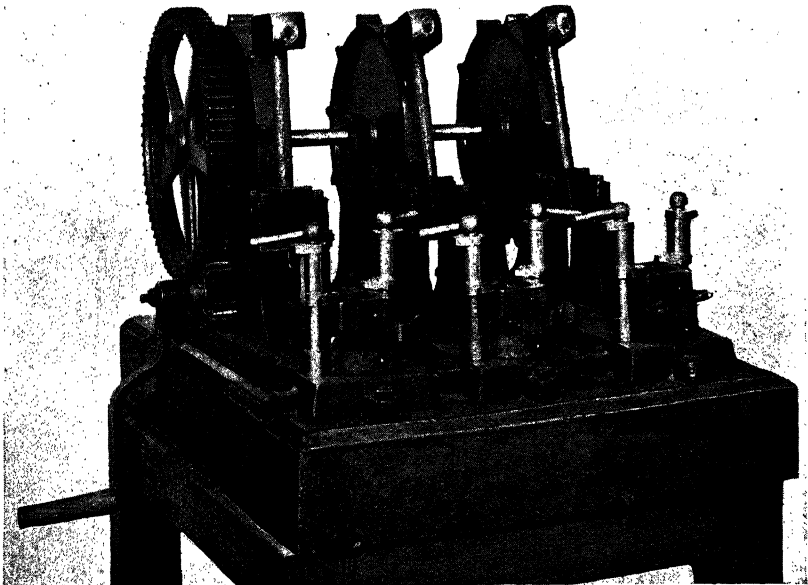


Fig. 240.—Hammer for Tamping Briquettes.

uniformity. They do not, however, produce better results than an experienced gauger can obtain by the British standard method described later. The same remarks apply more or less to machines for mixing the mortar, such as is shown in *Fig. 242*; this is a Continental machine and is specified in the German specification for Portland cement, but it has met with little favour in England.

PORTLAND CEMENT

TABLE XV.

TENSILE STRENGTH AT SEVEN DAYS OF STANDARD 3 : 1 MORTAR.
(lb. per sq. in.)

Cement.	Compacted with hand spatula.	Compacted with hammer.
No. 1	540	437
No. 2	473	427
No. 3	548	417
No. 4	570	487
No. 5	513	445
No. 6	505	408
No. 7	630	493
No. 8	577	435

Table XV is a comparison of tests made by the same experienced gauger of a number of cements. In one case the briquettes were compacted with a spatula

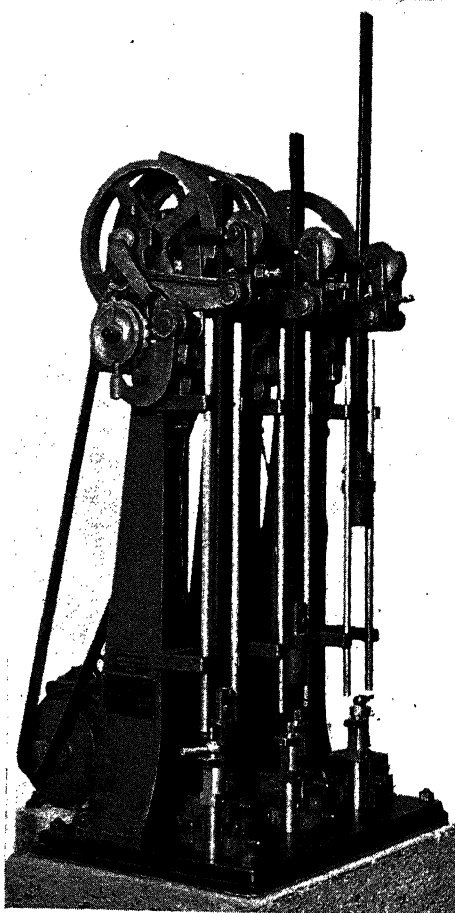


Fig. 241.—Hammer for Tamping Briquettes.

TABLE XVI

COMPARISON OF RESULTS OBTAINED BY DIFFERENT TESTING LABORATORIES ON FOUR RAPID-HARDENING PORTLAND CEMENTS. 24-HOUR TENSILE TESTS (1 cement : 3 standard sand).
(lb. per sq. in.)

Laboratory	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
Cement No. 1 :							
Average	292	238	283	277	243	357	546
Gauging water used (per cent.) .	7.81	9.25	9.0	9.0	9.375	8.75	8.375
Cement No. 2 :							
Average	157	131	126	152	135	187	331
Gauging water used (per cent.) .	8.12	9.0	8.5	8.375	8.5	8.5	8.0
Cement No. 3 :							
Average	127	119	123	161	160	189	350
Gauging water used (per cent.) .	8.12	8.75	8.5	8.375	8.375	8.5	8.0
Cement No. 4 :							
Average	178	203	219	245	282	312	427
Gauging water used (per cent.) .	8.12	9.0	9.0	8.25	8.125	8.25	7.75

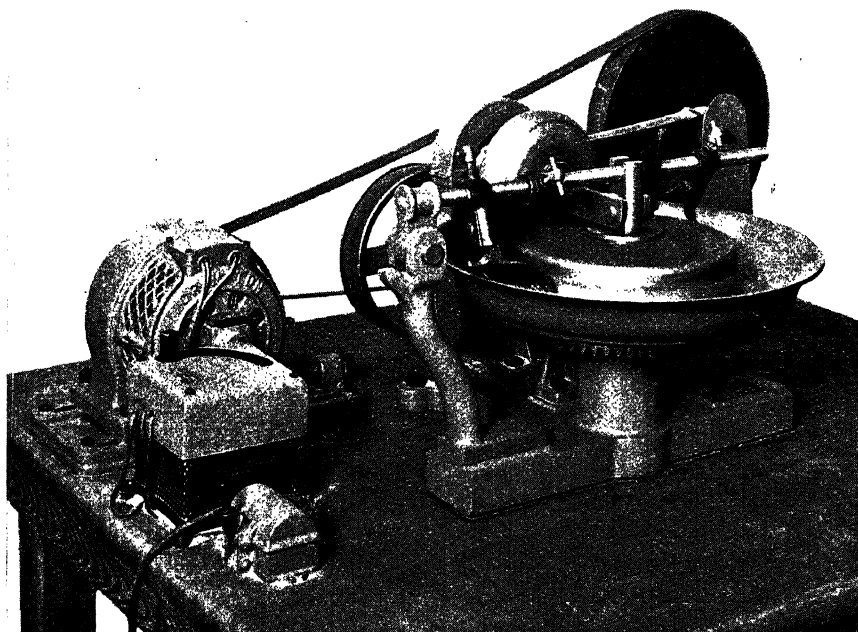


Fig. 242.—Steinbruck-Smeltzer Mortar Mixer.

in the British standard manner and in the other case they were compacted with the hammer illustrated in *Fig. 240*. Variations between different testers are apt to be more pronounced when tests are made at very early ages, and the introduction of rapid hardening cements, by calling for tensile tests at as short a period as twenty-four hours, has brought this fact into prominence. As an illustration of the differences which may be obtained even between experienced testers the figures in Table XVI are given. It should, however, be stated that these tests were made before

the inclusion in the British Standard Specification of a precise method of determining the quantity of water to be used for gauging.

Standard Test for Tensile Strength (Cement and Sand Mortar)

The British Standard Specification requires that in testing Portland cement for tensile strength the test shall be carried out as follows.

"The ultimate tensile stress of cement and sand shall be ascertained from briquettes of the shape shown (*Fig. 243*). The briquettes shall be prepared in the following manner :

"A mixture of cement and sand in the proportion of one part by weight of cement to three parts by weight of the standard sand specified shall be gauged with water, the percentage of water to be used being determined by the formula $\frac{1}{4}P + 2.50$ where P is the percentage of water required to produce a paste of normal consistency.*

"The mixture, gauged as above, shall be evenly distributed in moulds of the form required to produce briquettes of the shape shown (*Fig. 245*), each mould

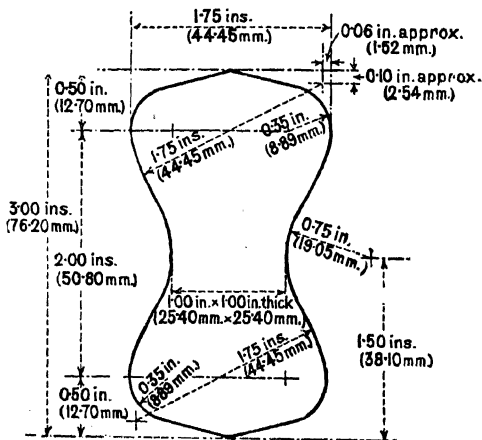


Fig. 243.—Standard Briquette (uniform thickness of 1 in. throughout).

resting upon a non-porous plate. After filling a mould a small heap of the mixture shall be placed upon that in the mould and beaten down with the standard spatula (*Fig. 244*) until the mixture is level with the top of the mould. This last operation shall be repeated on the other side and the mixture beaten down until water appears on the surface; the flat only of the standard spatula is to be used, and no other instrument or apparatus is to be employed for this operation. The briquettes shall be finished off in the moulds by smoothing the surface with the blade of a trowel.

"Clean appliances shall be used for gauging, and the temperature of the water and that of the test room at the time when the above operations are being performed shall be from 58 to 64 deg. F. (except for hot climates).

"The briquettes shall be kept at a temperature of 58 deg. F. to 64 deg. F. in an atmosphere of at least 90 per cent. relative humidity for 24 hours after gauging, when they shall be removed from the moulds and immediately submerged in clean fresh water, and left there until taken out just prior to breaking. The water in which

* Normal consistency is defined on page 290.

they are submerged shall be renewed every seven days, and maintained at a temperature of between 58 and 64 deg. F. After they have been so taken out and until they are broken the briquettes shall not be allowed to become dry.

"The briquettes shall be tested for ultimate tensile stress at the periods after gauging mentioned below. Six briquettes shall be tested at each period, and the ultimate tensile stress shall be the average ultimate tensile stress of the six briquettes for such period. The briquettes to be tested shall be held in strong metal jaws of the shape shown (*Fig. 245*) and the load steadily and uniformly applied, starting from zero and increased at the rate of 100 lb. per sq. in. of section in 12 seconds.

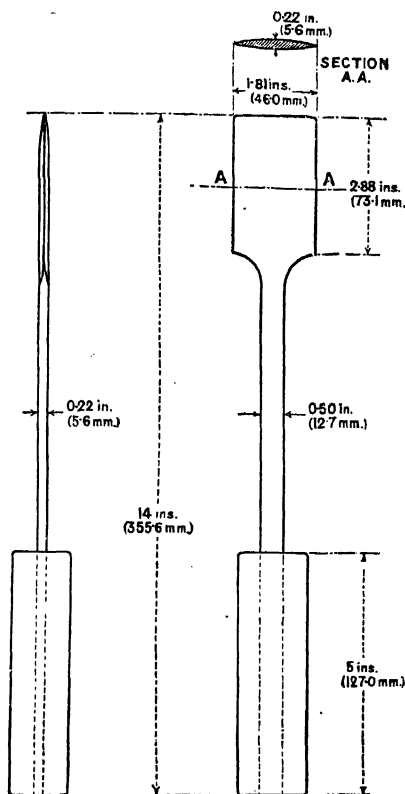


Fig. 244.—Standard Spatula.

"The ultimate tensile stress of the briquettes shall be as follows :

"ORDINARY PORTLAND CEMENT.—3 days (72 hours), not less than 300 lb. per square inch (21.09 kg. per sq. cm.). 7 days, an increase on the ultimate tensile stress at three days and not less than 375 lb. per square inch (26.37 kg. per sq. cm.).

"RAPID-HARDENING PORTLAND CEMENT.—1 day (24 hours), not less than 300 lb. per square inch (21.09 kg. per sq. cm.). 3 days (72 hours), an increase on the ultimate tensile stress at 1 day and not less than 450 lb. per square inch (31.63 kg. per sq. cm.).

"STANDARD SAND.—The standard sand shall be obtained from Leighton Buzzard, shall be of the white variety, and shall be thoroughly washed and dried. Its loss of weight on extraction with hot hydrochloric acid shall not be more than 0.25 per cent. The sand shall pass through a B.S. test sieve No. 18 and be retained

on a B.S. test sieve No. 25. The sieves shall be prepared from wire-cloth complying with the requirements of Table I of the British Standard Specification for Test Sieves (B.S.S. No. 410). The wire-cloth shall be woven (not twilled), and carefully mounted on the frames without distortion. The sieving surface shall be not less than 50 sq. in. (322.58 sq. cm.) and the depth of the sieves shall be not less than $2\frac{3}{4}$ in. (69.85 mm.) measured from the surface of the wire-cloth."

The nominal dimensions and tolerances for wire-cloths for sieves for preparing standard sand are given in Table XVII. The maximum tolerances for occasional large apertures, if present, expressed as percentages of the nominal dimensions for side of aperture in either direction must not exceed 20 per cent.

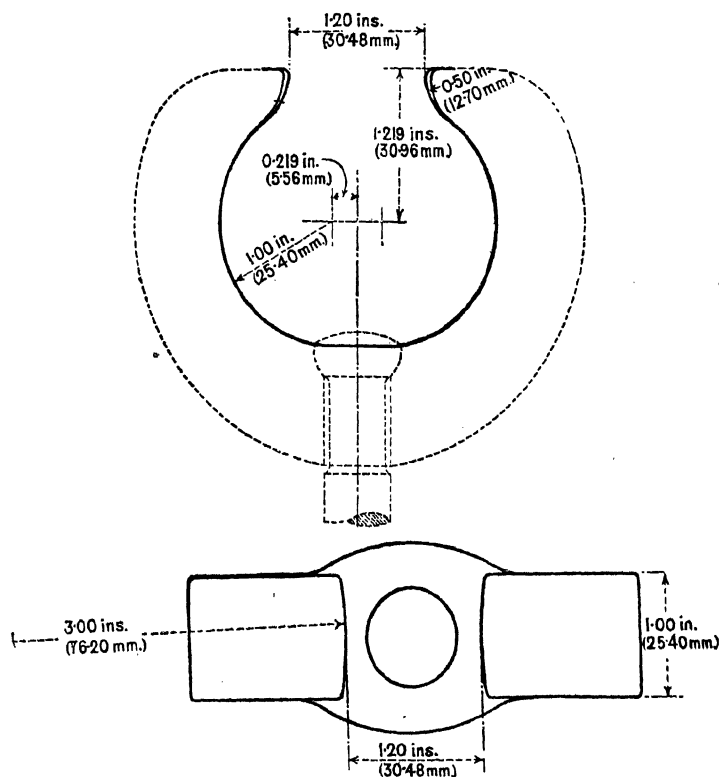


Fig. 245.—Standard Jaws for Tensile Testing Machine.

In the preparation of briquettes all moulds should be made preferably of gun-metal and of the standard shape, and the gauging of each briquette should be carried out in exactly the same manner. As the reliability of the tensile strength test depends mainly upon the preparation of the briquettes it is necessary that precautions be taken so that the personal equation is so far as possible eliminated. Care should be taken that the moulds have been properly cleaned and are placed on small non-porous plates (iron, slate, or glass).

For the test, the required quantities of cement and sand for each briquette are weighed (usually 150 gr. of sand and 50 gr. of cement) and turned out in a heap on the gauging slab, where they are thoroughly mixed dry. After the heap has been hollowed out into a crater, the exact amount of water which it has been previously

determined will provide the consistency required according to the Standard Specification is gradually poured on. The mortar is then thoroughly trowelled and the mould filled, beating down the material with the standard spatula (*Fig. 246*) so that it is solid and free from air spaces ; finally the top side of the briquette is trowelled off flush.

TABLE XVII

DIMENSIONS OF STANDARD WIRE-CLOTHS FOR SIEVES FOR
PREPARING STANDARD SAND.

B.S. Mesh No. (nominal meshes per linear inch).	Nominal size of aperture (side of square).		Nominal diameter of wire.		Standard wire gauge.	Approx. screening area. Per cent.	Tolerance on average aperture, plus or minus. Per cent.
	in.	mm.	in.	mm.			
25	0.0236	0.599	0.0164	0.417	27	35	5
18	0.0336	0.853	0.022	0.559	24	36	5

During setting the briquettes must be placed in a damp box or cupboard or covered with a wet cloth so as to obtain the required humidity, and allowed to remain for twenty-four hours in a place free from vibration. A briquette thus hardened in a saturated atmosphere and kept free from hot or dry draughts may

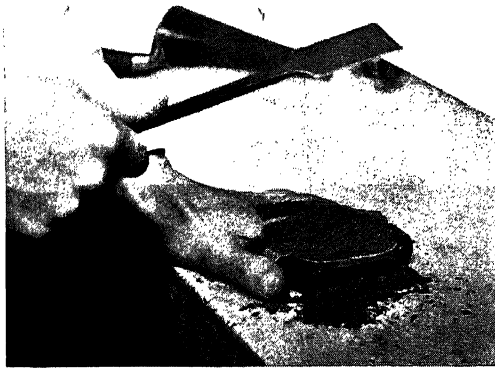


Fig. 246.—Compacting Briquette with Standard Spatula.

be relied upon to be stronger, and the testing results more uniform, than is the case where by improper treatment the water is evaporated from the mortar too quickly. When the briquettes are thoroughly set they should be removed from the mould and immersed in water at the standard temperature until required for testing.

Typical Testing Machines

Some of the testing machines generally used in this country are illustrated ; *Fig. 247* shows the "Adie" testing machine with automatic regulator. In this

machine the briquette is inserted in the clips and by the use of the automatic regulator the weight is moved gently along until the briquette has broken, the strain being then read on the lever. The automatic regulator gives a uniform rate of travel to the weight, so that all strains are applied at the standard rate of 500 lb. per minute, but this can be altered to any speed required by means of a cock in the piston. It is also self-acting, and when the test is started it needs no interference whatever; directly the briquette breaks the weight is held fast by means of a clutch or brake until released.

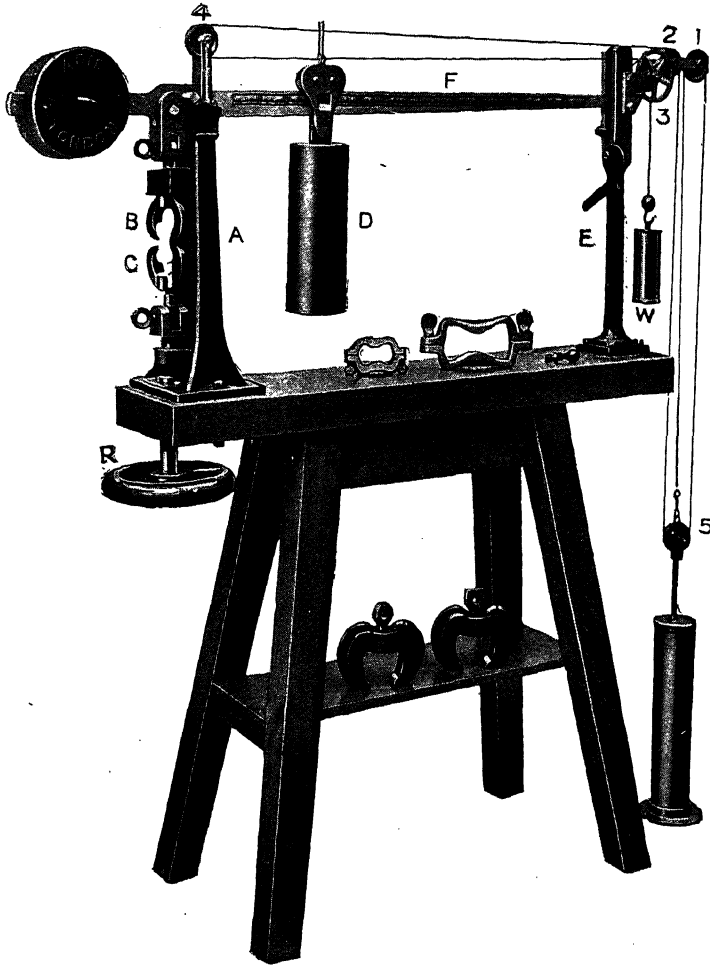


Fig. 247.—Adie Tensile Testing Machine.

Salter's machine (Fig. 248) consists of a japanned cast-iron column carrying a pair of compound levers having a combined leverage of 50 to 1. A sliding balance weight for setting the levers in equilibrium is fitted to the upper lever. The upper jaw, to receive the cement briquette, is suspended from a knife edge on the lower lever; the lower jaw is attached to the base of the column, and is adjustable by means of a screw and a small handwheel. The supply of shot to the bucket is automatically cut off the moment the briquette breaks. To use the machine, the levers are set "floating" by means of the sliding balance weight; once it has been set

this need not be touched. The briquette is next placed in the jaws, the bucket is hung on the bridge, and the hand-wheel screwed up until the top side of the lever from which the shot is suspended is about half an inch from the top of the guide. The handle of the shot receptacle is adjusted to apply the load at 500 lb. per minute. When the briquette breaks the supply of shot is cut off.

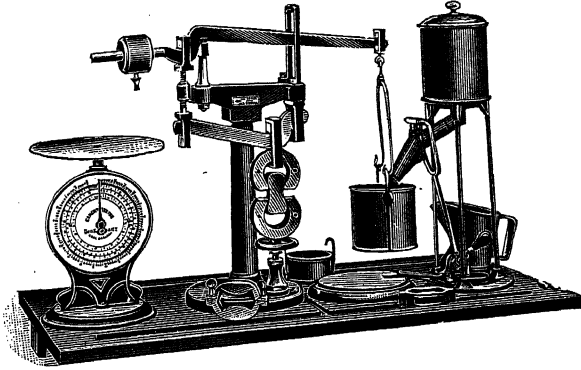


Fig. 248.—Salter Tensile Testing Machine.

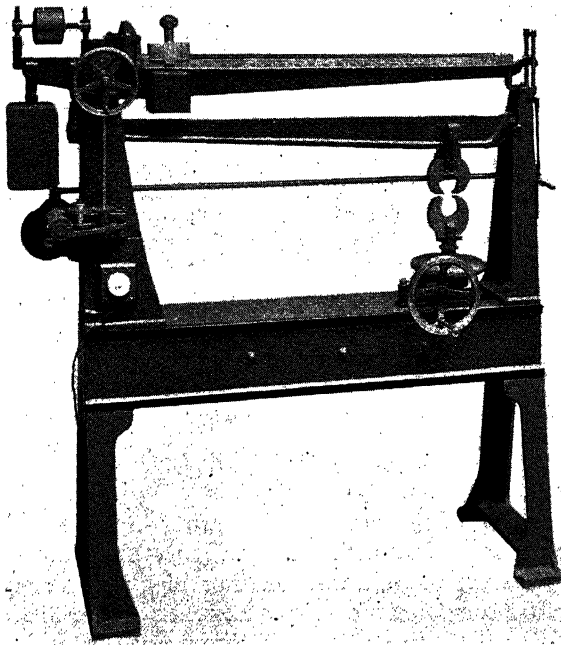


Fig. 249.—Macklow-Smith Tensile Testing Machine.

There are other machines used for testing cement for tensile strength, but the two mentioned are typical of machines which have been used for many years. A machine of a later and perhaps more elaborate design incorporating improvements on some earlier types is the Macklow-Smith machine illustrated in *Fig. 249*.

Growth of Strength

In regard to tests of cement mortar designed to show the growth of strength with age, the writer has made many series of such tests, usually extending over a period of years. Standard mortars made from various cements all show the same characteristic fluctuations in tensile strength at intermediate dates, with a generally upward tendency, and a typical curve is given in *Fig. 250*. A study of the percentage of gain in strength for various periods of time illustrates clearly the important fact that while what were good standard cements of some years ago took an appreciable period to acquire any great strength, the same degree of strength is attained in a very much shorter period by present-day cements, and, of course, still more quickly with rapid-hardening cements.

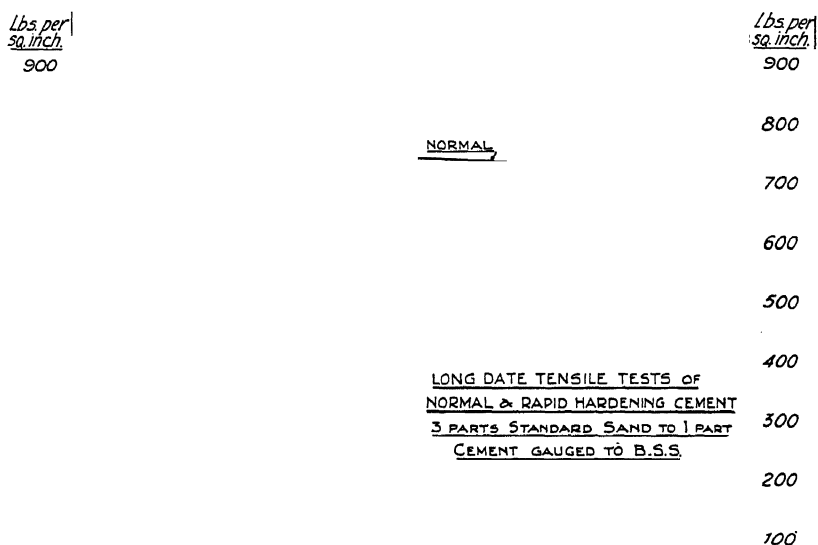


Fig. 250.

The tensile strength of mortars decreases with an increase in the percentage of voids, since strength increases with density. It has therefore to be kept in mind that a sand of uniform size of grain will contain a high percentage of voids and will require more cement for maximum density. For the purpose of securing uniformity of testing standard sand consists of practically one size of grain, and is therefore inferior in this respect to good natural sand for constructional purposes, as the uniform size of grain gives a harsh mortar high in voids.

Although it may be said that the tensile strength of Portland cement is not an ideal test, and that in practice it leads to somewhat divergent results, yet on the whole it has been shown that the better the cement as shown by the standard test the stronger will be the concrete when it is mixed with aggregate. It is therefore interesting, in considering the progress which has been made in the quality of cement

during the last thirty years, to study the comparison in Table XVIII of the increasingly stringent requirements of successive revisions of the British Standard Specification as regards the tensile strength of 3 : 1 standard sand mortar.

TABLE XVIII

COMPARISON OF TENSILE STRENGTH REQUIREMENTS OF B.S.S., 1904 TO 1940.

Issue of B.S.S.	lb. per sq. in.				Increase from 7 to 28 days must not be less than
	1 day.	3 days	7 days.	28 days.	
1904 .	No test	No test	120	225	20%.
1907 .	do.	do.	150	250	20%.
1910 .	do.	do.	150	250	25%, 15%, 10%, or 5%, according to 7-day result.
1915 .	do.	do.	200	No test do.	Breaking strength } + { $\frac{10,000 \text{ lb.}}{\text{Breaking strength}}$ at 7 days. } at 7 days.
1920 .	do.	do.	200		do.
1925 .	do.	do.	325		do.
1931 .	do.	300	373		28-day test discontinued.
1940 .	do.	300	375		
do. .	300*	450*			

For rapid-hardening Portland cement.

CHAPTER XXVI

COMPRESSION AND TRANSVERSE TESTS

THE tensile test of cement mortar made with standard sand indicates whether a cement is satisfactory or not. There are, however, so many factors which determine the strength of concrete that if it is desired to get an indication of what this will be tests must be made with the actual ingredients which will be used, and this can best be done by a compression or transverse test. For this purpose it is also important that the mixing, tamping, and storage of the specimens should be conducted under the practical conditions which will occur when the concrete is made and used, but, within the limits imposed by those conditions, procedure should be standardised as much as possible. It must be appreciated, however, that under such conditions the results obtained cannot be a reliable guide to cement quality alone.

The ratio between the tensile and crushing strength of concrete is not invariably constant. The compressive strength increases more rapidly with age than does the tensile strength. In both the tensile and compression tests results will not be obtainable before the cement has set hard, because whilst in the "green" state immediately after the final set the test blocks will not bear any appreciable strain; but results are ascertainable within 24 hours of the final setting of the cement for most present-day cements of a rapid-hardening character.

Compression Tests

The compression test of standard-sand-cement-mortar is specified in the cement specifications of about half the countries of the world which have adopted official standards for cement. The minimum resistance required varies between 1,700 and 3,200 lb. per sq. in. at seven days and between 2,000 and 5,000 lb. at twenty-eight days; these wide limits are due in the main to varying ideas of consistency and methods of making and storing specimens. The British Standard test for compression is performed on a cube with sides of 50 sq. cm. area (2.78 in.). Cylinders are sometimes used, but they appear to possess no great advantage, while they have a disadvantage in the actual crushing operation.

Before the stipulation in the 1940 edition of the British Standard Specification that compression test cubes must be consolidated by vibration, it was customary to consolidate them by hammer, and this method is in use in other countries. The British Standard spatula for making mortar briquettes is useless for the purpose, and it is usual to use a block of wood or metal which just fits into the mould, and to hammer this either by hand or machine (see *Figs. 251 and 252*). After the preparation of the block by this process, the top and bottom faces are trowelled off and the specimen put aside to set for a period of 24 hours under the standard humidity and temperature conditions for briquettes, afterwards being removed from the mould and placed in water, as with briquettes. The immersion lasts until the test takes place, and each block must be tested immediately it is taken from the water—in short, the procedure follows the British Standard Specification for tensile tests.

The compressive test in the 1940 edition of the British Standard Specification is described as follows:

"The compressive strength of cement and sand shall be ascertained from cubes

having a length of side of 2.78 in. (the area of face equals 50 sq. cm.). The cubes shall be prepared in the following manner.

"A mixture of cement and sand in the proportions of one part by weight of cement to three parts by weight of standard sand shall be mixed dry with a trowel on a non-porous plate for one minute and then with water until the mixture is of a uniform colour, the percentage of water being 10 per cent. by weight of the dry materials. Should the time taken to obtain a uniform colour exceed four minutes the mixture shall be rejected and the operation repeated with a fresh quantity of cement, sand, and water.

"The material for each cube shall be mixed separately and the quantities of cement, sand, and water, for both ordinary and rapid-hardening Portland cement shall be as follows : Cement, 185 gr. ; sand, 555 gr. ; water, 74 gr. When so desired,



Fig. 251.—Hand Ramming.

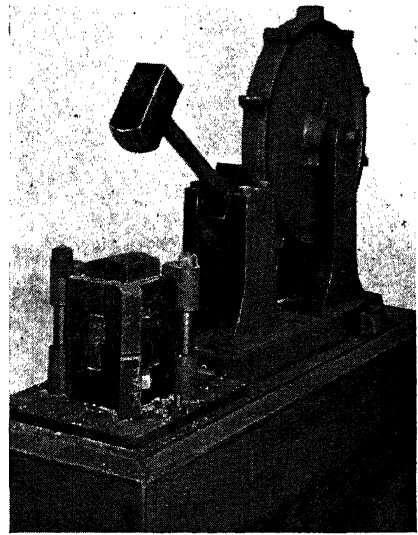


Fig. 252.—Machine Ramming.

3-in. cubes may be used for the test, in which case the quantities shall be as follows : Cement, 235 gr. ; sand, 703 gr. ; water, 94 gr.

"Immediately after the mixing, the mortar shall be placed in the hopper of the cube mould in one portion and shall be compacted by vibration. The vibrating machine (Fig. 253) shall have a frequency of 12,000 vibrations per minute (plus or minus 400 v.p.m.) with an amplitude of 0.0022 in. The mould shall be of metal accurately machined and with parallel faces and together with its baseplate shall be firmly held on the table of the vibration machine. A hopper of suitable size and shape shall be securely attached to the mould to facilitate filling, and this hopper shall not be removed until completion of the vibrating period.

"The mould filled with mortar shall be vibrated for two minutes at full speed and shall not otherwise be finished by trowel or by hand. The faces and joints of

the mould shall be covered with a film of petroleum jelly and the joints shall be tightly made so as to ensure that no water escapes during the vibration.

"Clean appliances shall be used for mixing and the temperature of the water and that of the test room at the time when the above operations are being performed shall be from 58 deg. F. to 64 deg. F. (14.4 deg. C. to 17.8 deg. C.).

"The cubes shall be kept at a temperature of 58 deg. F. to 64 deg. F. in an atmosphere of at least 90 per cent. relative humidity for 24 hours after completion of vibration, when they shall be removed from the moulds and immediately submerged in clean fresh water, and left there until taken out just prior to breaking. The water in which they are submerged shall be renewed every seven days and

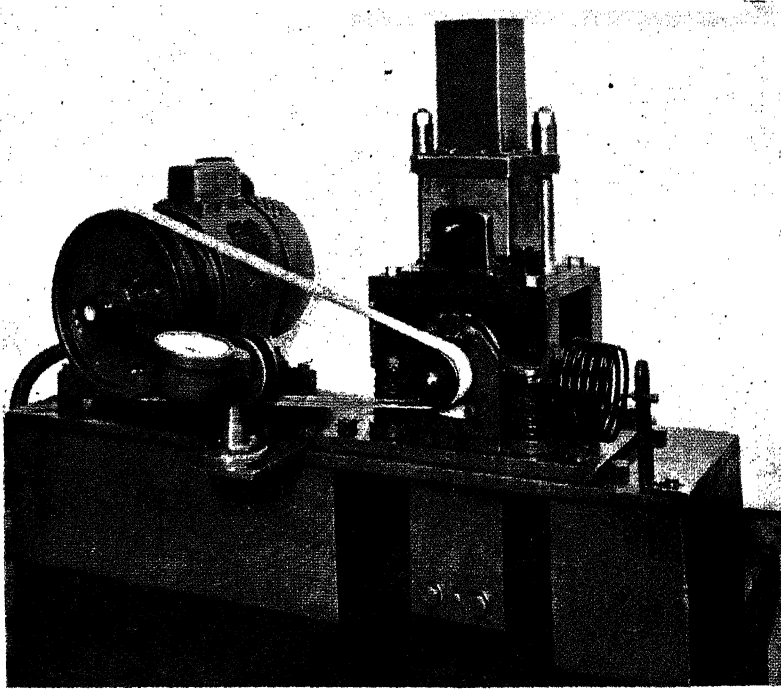


Fig. 253.—Vibrating Machine for Compression Test.

maintained at a temperature of between 58 deg. F. and 64 deg. F. After they have been so taken out and until they are broken the cubes shall not be allowed to become dry.

"CRUSHING.—The cubes shall be tested for compressive strength at the periods mentioned below, which shall be reckoned from the completion of vibration.

"Ordinary Portland cement, 3 days (72 hours) and 7 days.

"Rapid-hardening Portland cement, 1 day (24 hours) and 3 days (72 hours).

"The cubes shall be tested on their sides without any packing between the cube and the steel platens of the testing machine. One of the platens shall be carried on a ball and shall be self-adjusting and the load shall be steadily and uniformly applied starting from zero at a rate of 5,000 lb. per sq. in. per minute. The compressive strength shall be calculated from the crushing load and the average area over which the load is applied.

"The compressive strength of the cubes shall be as follows:

"Ordinary Portland cement: 3 days (72 hours), not less than 1,600 lb. per sq. in. (112.5 kg. per sq. cm.); 7 days, an increase on the compressive strength at 3 days and not less than 2,500 lb. per sq. in. (175.8 kg. per sq. cm.).

"Rapid-hardening Portland cement: 1 day (24 hours), not less than 1,600 lb. per sq. in. (112.5 kg. per sq. cm.); 3 days (72 hours), an increase on the compressive strength at 1 day and not less than 3,500 lb. per sq. in. (246.1 kg. per sq. cm.)."

The vibrating machine specified consists of a frame mounted on light springs to carry the cube mould, and a revolving shaft provided with an eccentric. By means of a balance weight beneath the baseplate attached rigidly to the frame, the centre of gravity of the whole machine, including the cube and mould, is brought to the centre of the eccentric shaft. In consequence of this the revolving eccentric imparts an equal circular motion to all parts of the machine and mould, the motion

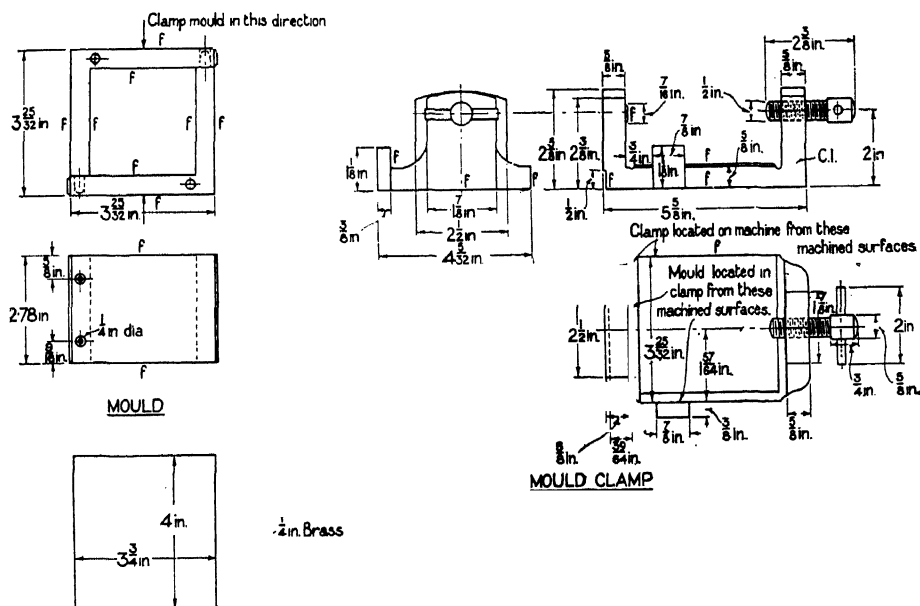


PLATE TO FORM BOTTOM OF MOULD

Fig. 254.—Mould and Clamp for Compression Test with Vibrating Machine.

being equivalent to equal vertical and horizontal simple harmonic vibrations 90 deg. out of phase. The minimum running speed of the machine is well above its natural frequency on its supporting springs, so that the amplitude of vibration is independent of the speed. The machine is specified to be constructed to comply with the following requirements. Total weight of machine on its supporting springs (excluding weight of solid eccentric but including weight of hopper, mould, and cube) 64 lb. approximately; weight of solid eccentric, 0.7 lb. approximately; eccentricity of eccentric, 0.2 in.; normal running speed of eccentric shaft, 12,000 (± 400) r.p.m. A machine of the type described is shown in Fig. 253, and a mould, clamp, and hopper suitable for use with the machine are shown separately in Figs. 254 and 255.

CRUSHING TEST CUBES.—Machines for carrying out compression tests are usually hydraulically operated, oil being used as the pressure medium (see Fig. 256). Other

box or other lining for tightening the pistons, the friction will be smaller rather than greater when the machine is loaded because of the slight widening of the cylinder. A good hydraulic machine of the latter type is as accurate as a good lever machine ; in respect to wear and tear it is almost indestructible—in fact, the machine will improve by frequent use in consequence of the wearing away of any roughness on the cylinders and pistons. No special foundation is normally required for hydraulic crushing machines, save only that the floor should be strong enough to carry the weight. Where a stuffing box or other piston lining is used the efficiency of an hydraulic machine is about 92 to 98 per cent. of the recorded load.

It is necessary that the distribution of the load over the top and bottom surfaces of the block should be quite uniform. Cylinders may be bedded by using plaster of Paris, the plaster being levelled on the two ends to a thickness of about a quarter

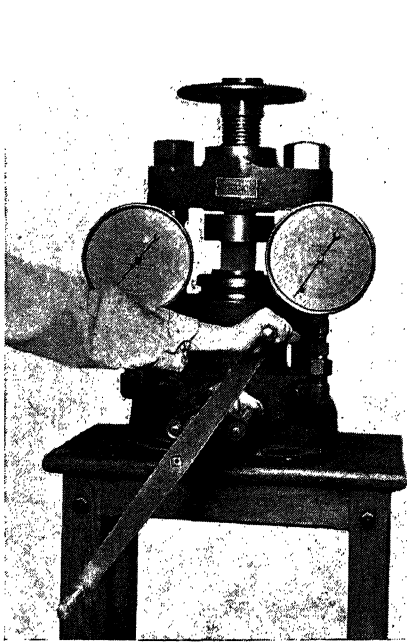


Fig. 256.—Hydraulic Crushing Machine for 50 sq. cm. Cubes.

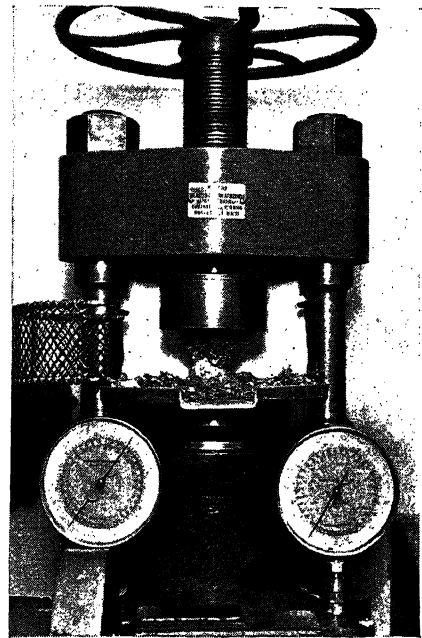


Fig. 257.—Hydraulic Crushing Machine for 6-in. Cubes.

of an inch. Leather, linoleum, lead, and other forms of packing are also used. Alternatively the ends may be ground flat and parallel. It is, however, usually preferable to make cubes in metal moulds, as described in the British Standard Specification, with plane and parallel sides of such accuracy that the specimens may be crushed on two of the sides which have been in contact with the mould without any packing, and this simple and convenient way of securing an even bedding in the testing machine is a strong point in favour of cubes as compared with cylinders. A typical failure of a concrete cube tested to destruction under these conditions is shown in *Fig. 257*.

WORKS TEST CUBES.—The compression strengths obtained from mixtures of cement and sand, or cement, sand and stone, may vary within very wide limits due to the proportions of the mix, the amount of water used, thoroughness of mixing,

method of consolidation, size, shape, and grading of the aggregate, physical structure of the aggregate, construction of the mould, size, shape, and age of the specimen, method of storage, method of testing, and temperature and atmospheric conditions. In dealing with compression tests made of concrete as used in constructional work, all these points must be kept in mind. The precise control which is obtainable in a laboratory is usually lacking in such cases, and, therefore, such tests are inherently less reliable and must be viewed more tolerantly.

The Building Research Station's standard method of making compression tests of concrete sampled during the progress of the work is as follows :

" **SIZE OF TEST CUBES AND MOULDS.**—The test specimens shall be 6-in. cubes. The moulds shall be of steel or cast iron, with inner faces accurately machined in order that opposite sides of the specimen shall be plane and parallel. Each mould shall be provided with a base plate having a plane surface and of such dimensions as to support the mould during filling without leakage and preferably attached by



Fig. 258.—Rodding Concrete Cubes.

springs or screws to the mould. Before placing the concrete in the mould both the base plate and the mould shall be oiled to prevent sticking of the concrete.

" **SAMPLING OF CONCRETE.**—Wherever practicable concrete for the test cubes shall be taken immediately after it has been deposited in the work. Where this is impracticable samples shall be taken as the concrete is being delivered at the point of deposit, care being taken to obtain a representative sample. All the concrete for each sample shall be taken from one place. A sufficient number of samples, each large enough to make one test cube, shall be taken at different points so that the test cubes made from them will be representative of the concrete placed in that portion of the structure selected for tests. The location from which each sample is taken shall be noted clearly for future reference.

" In securing samples the concrete shall be taken from the mass by a shovel or similar implement and placed in a large pail or other receptacle, for transporting to the place of moulding. Care shall be taken to see that each test cube represents the total mixture of concrete from a given place. Different samples shall not be

mixed together but each sample shall make one cube. The receptacle containing the concrete shall be taken to the place where the cube is to be moulded as quickly as possible and the concrete shall be slightly re-mixed before placing in the mould.

"CONSISTENCY.—The consistency of each sample of concrete shall be measured, immediately after re-mixing, by the slump test (*Fig. 259*). Providing that care is taken to ensure that no water is lost the material used for the slump tests may be re-mixed with the remainder of the mix before making the test cube.

"COMPACTING.—Concrete test cubes shall be moulded by placing the fresh concrete in the mould in three layers, each layer being rammed (*Fig. 258*) with a steel bar 15 in. long and having a ramming face of 1 in. square and a weight of 4 lb. For mixes of $1\frac{1}{2}$ in. slump or less, 35 strokes of the bar shall be given for each layer; for mixes of wetter consistency the number may be reduced to 25 strokes per layer.

"CURING.—The test cubes shall be stored at the site of construction, at a place free from vibration, under damp sacks for 24 hours ($\pm\frac{1}{2}$ hour) after which

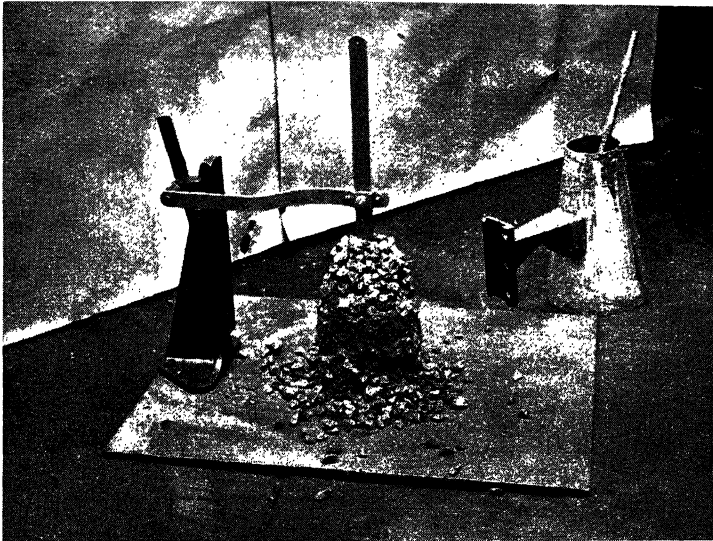


Fig. 259.—Slump Test.

time they shall be removed from their moulds, marked and buried in damp sand until the time for sending to the testing laboratory. They shall then be well packed in damp sand or other suitable damp material and sent to the testing laboratory, where they shall be similarly stored until the date of test. Test cubes shall be kept on the site for as long as practicable but at least three-fourths of the period before test except for tests or ages less than seven days. The temperature of the place of storage on the site shall not be allowed to fall below 40 deg. F., nor shall the cubes themselves be artificially heated.

"RECORD OF TEMPERATURES.—A record of the maximum and minimum day and night temperatures at the place of storage of the cubes shall be kept during the period the cubes remain on the site.

"METHOD OF TESTING.—All compression tests on concrete cubes shall be made between smooth plane steel plates without end packing, the rate of loading being kept approximately at 2,000 lb. per square inch per minute. One compression plate

of the machine shall be provided with a ball seating in the form of a portion of a sphere, the centre of which falls at the central point of the face of the plate. All cubes shall be placed in the machine in such a manner that the load shall be applied to the sides of the cubes as cast."

SLUMP TEST.—The apparatus needed for the slump test is a sheet-metal truncated-cone mould, 12 in. high, 8 in. diameter at the base, and 4 in. diameter at the top, provided with handles at the sides (see *Fig. 259*), and a $\frac{5}{8}$ -in. bullet-nosed metal rod 2 ft. long. The mould is filled with concrete in layers of 3 in. at a time, each layer being prodded twenty-five times with the rod. After the third and last layer has been rodded and levelled, the mould is lifted off and the slump measured. Care must be taken to ensure that the concrete being tested is not caused to slump by vibration.

Transverse Tests

Little is now heard respecting transverse tests of Portland cement mortar and concrete, although the test is used for concrete products such as roofing tiles and paving slabs. Investigations have been made from time to time to determine

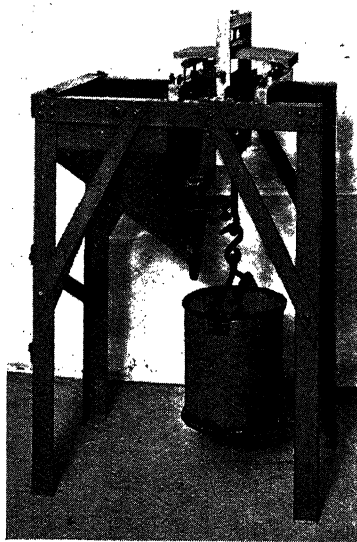


Fig. 260.—Transverse Test of Concrete Tile.

whether this test is useful as a laboratory check upon the quality of cements, but it has yet to be shown conclusively that the test offers advantages over the tensile strength test. It has at times been suggested that a transverse test should be incorporated in cement specifications, but this test would appear to have a greater sphere of usefulness in the testing of mortars and concretes whose composition makes them unsuitable for making up into the small briquettes necessary for the tensile test. The transverse testing of cement quality (as distinct from that of cement products) has therefore not received much official recognition, although for many years it has been used in an intermittent and experimental way. Its chief claim to consideration is perhaps the ease with which such a test can be conducted without

expensive machines, and the latitude it allows for variation of the dimensions of the specimens to be tested. It sometimes happens, moreover, that the transverse test is the only available method of testing, particularly with regard to concrete articles of the type mentioned, where a tensile or crushing test is clearly impracticable. A very simple arrangement of two knife edges upon which the article is to rest, together with a means of applying the load to the centre of the unsupported span of the article, can be made to give reliable results. In a case where the weights applied are multiplied by a lever arrangement, care must be taken that the load is applied perpendicularly and at right angles to the axis of the specimen.

The relation between the transverse test and tensile test of a given sample of cement varies as much with regard to conditions as does the relation between the tensile and crushing tests. In testing concrete the cross-section of the bar must depend to a large extent upon the size of the aggregate used, to avoid the possibility of any large piece of stone taking up a considerable proportionate area of the point under stress.

Transverse tests of small bars of standard mortar are somewhat unreliable unless carried out by a careful and experienced tester under properly controlled conditions, and, as already stated, the test finds its most useful field in determining the strength of small factory-made articles, such as roofing tiles, whose dimensions and shape prevent either a tensile or crushing test. *Fig. 260* shows the method of making such a test on roofing tiles.

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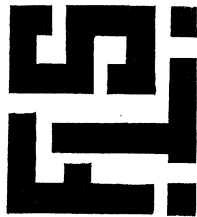


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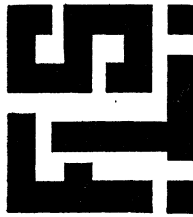
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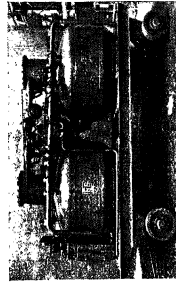
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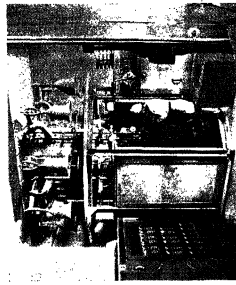
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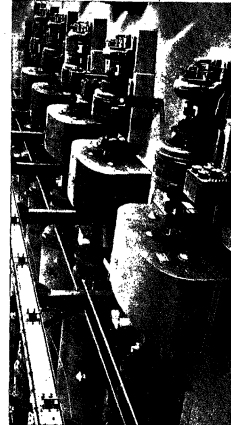
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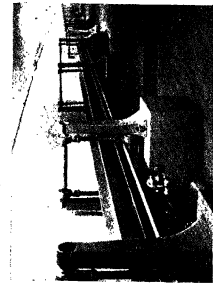
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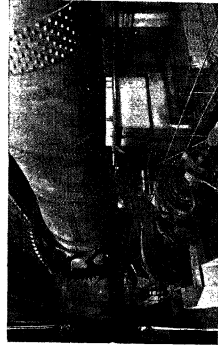
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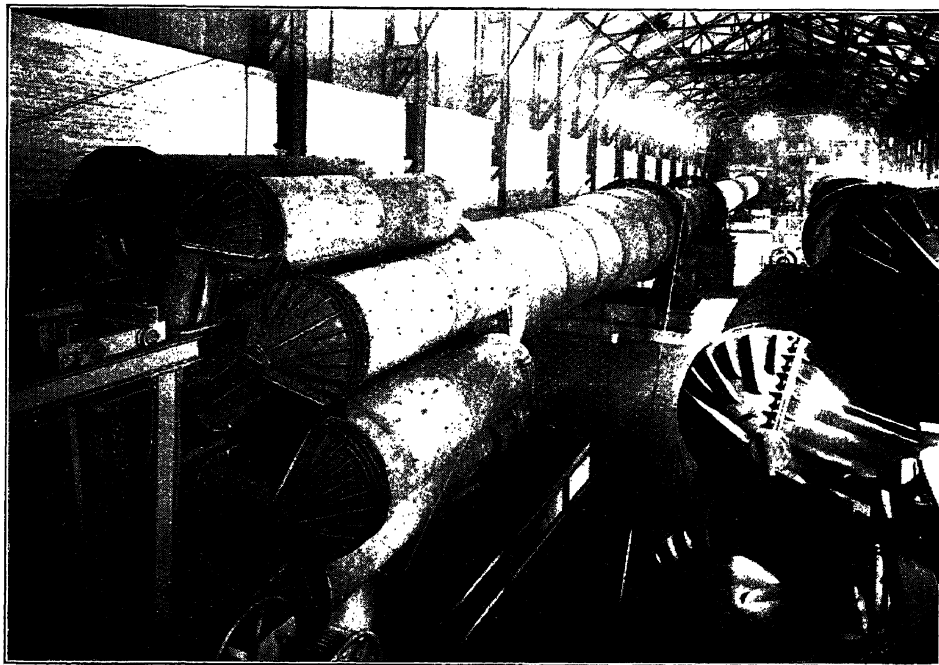
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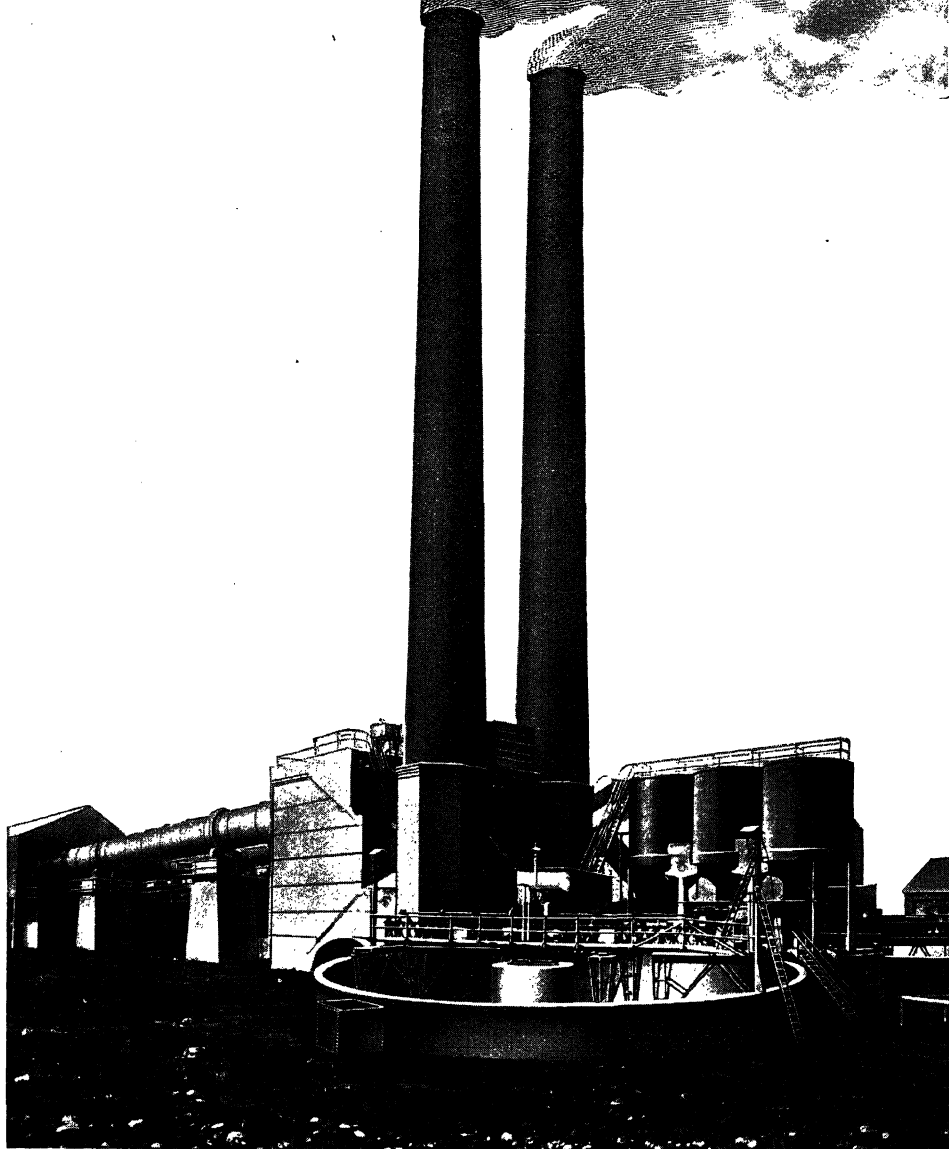
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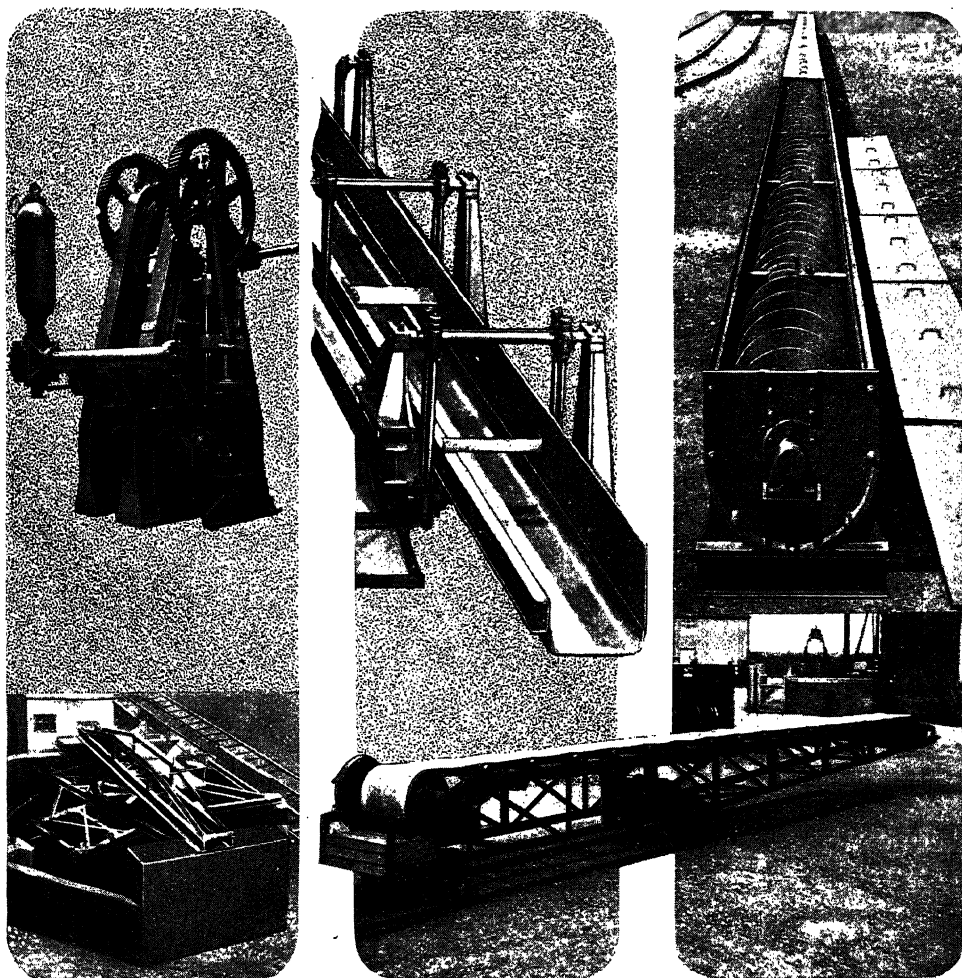
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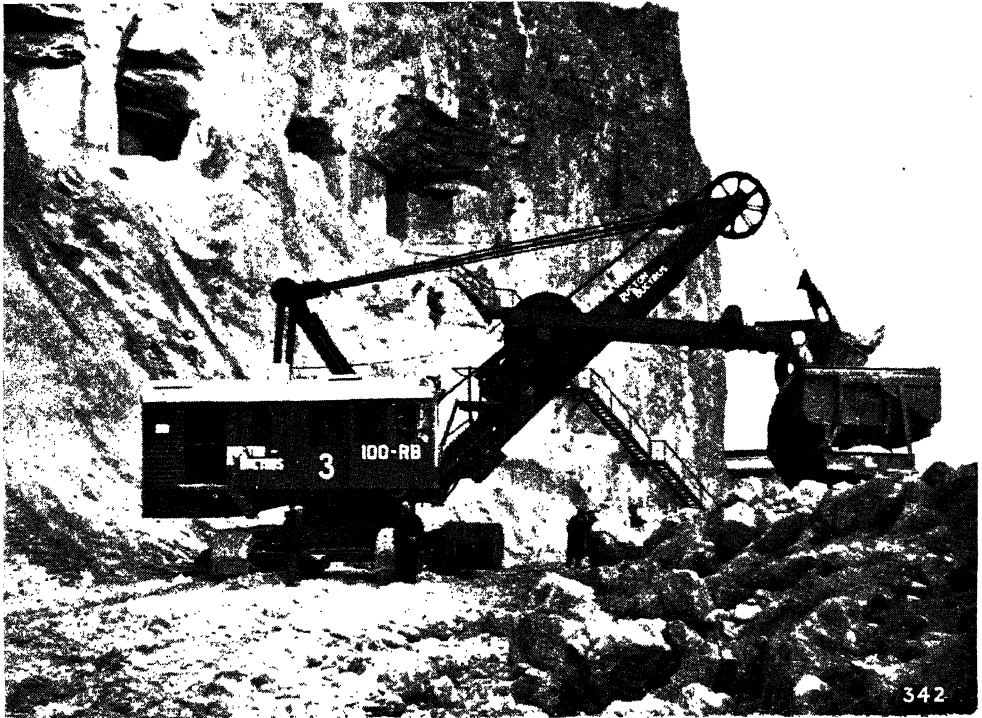
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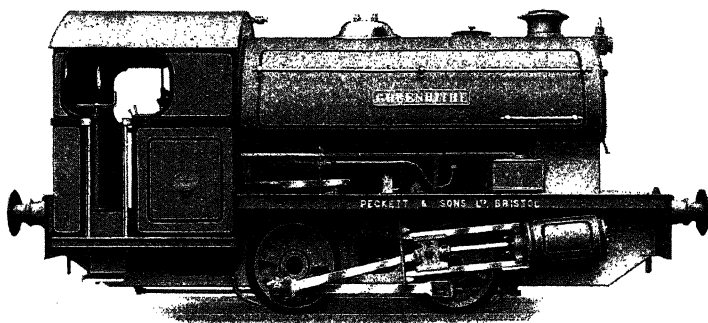
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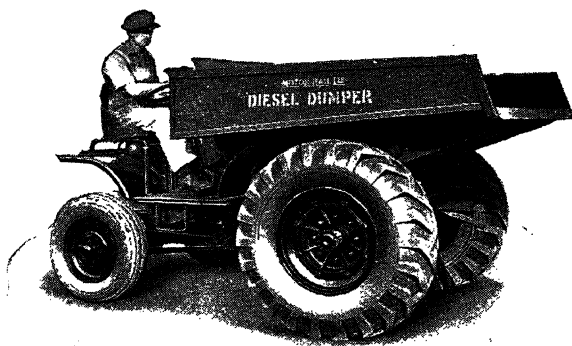
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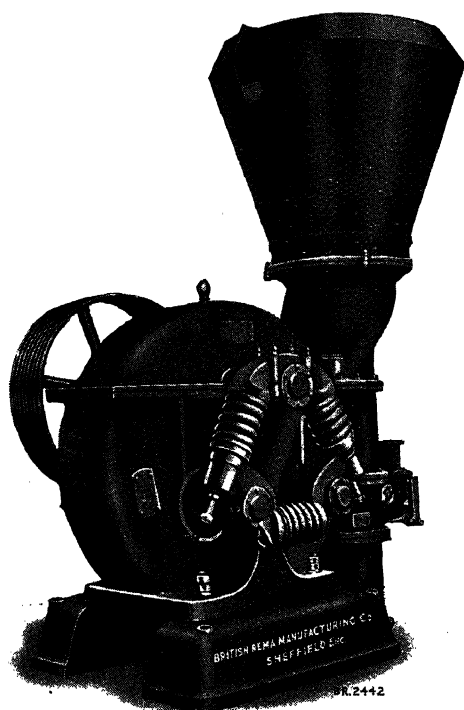
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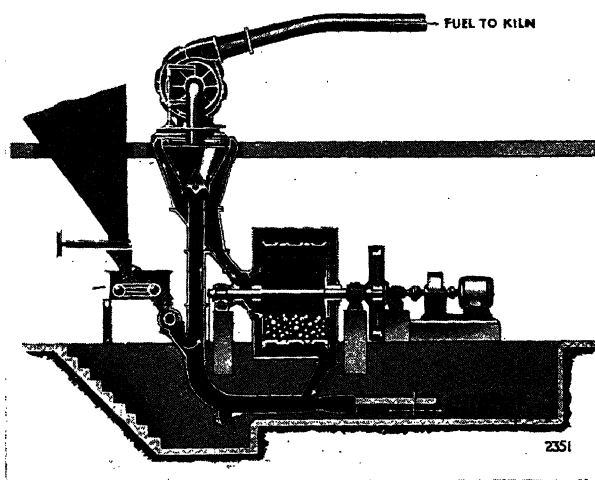
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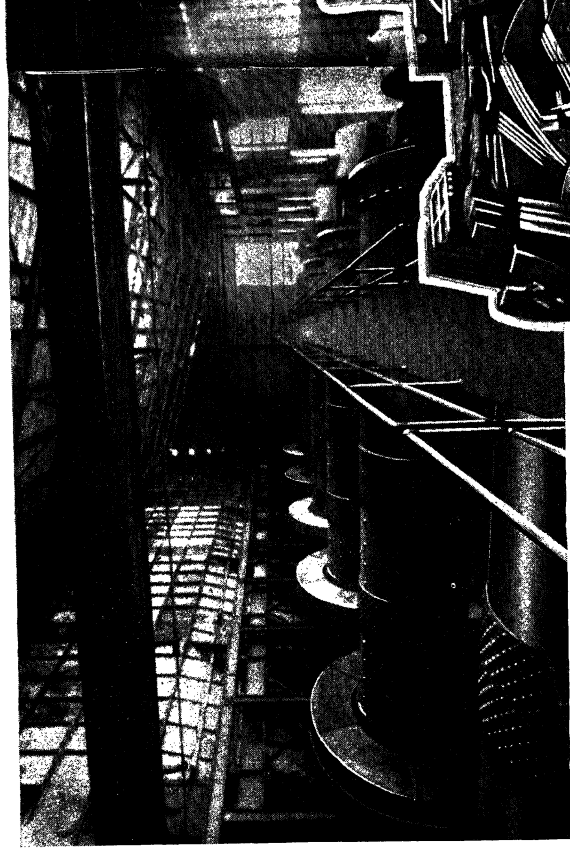
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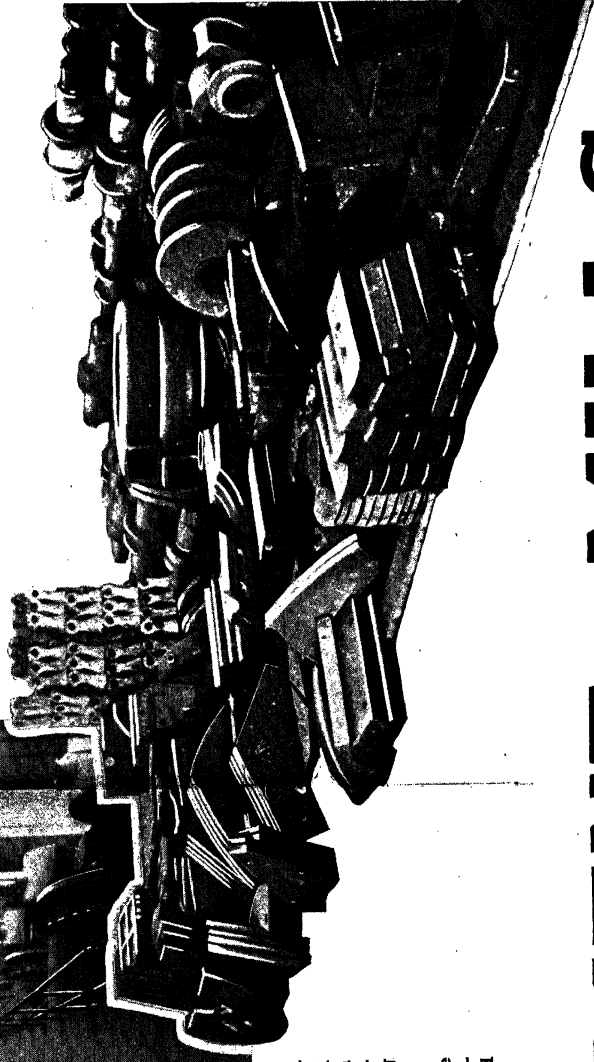
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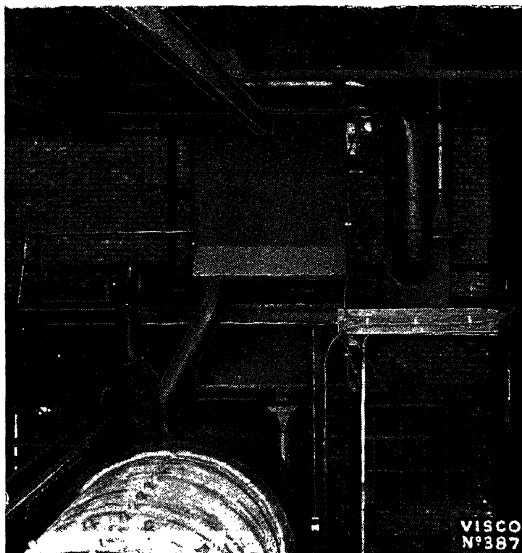
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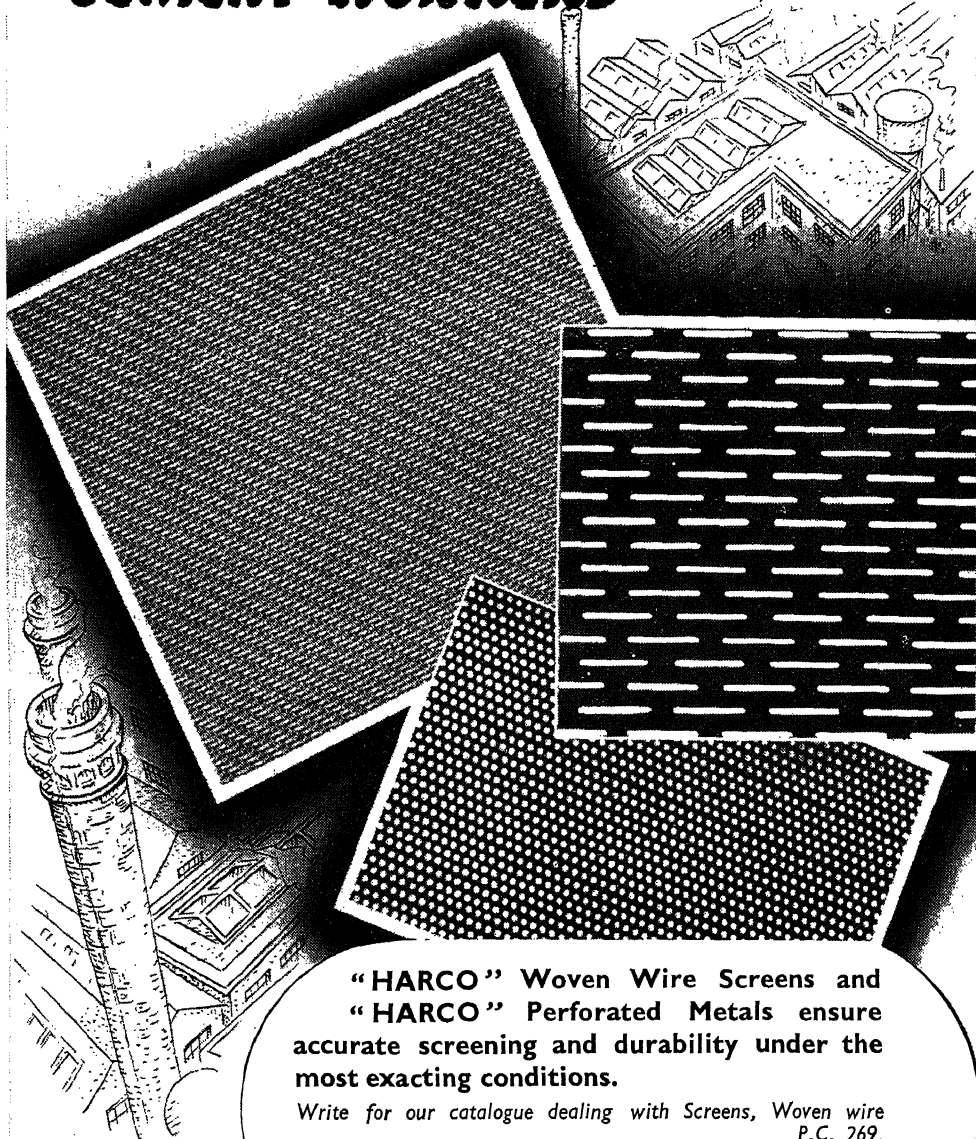
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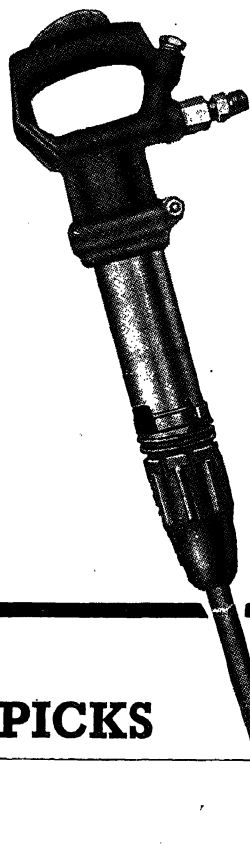
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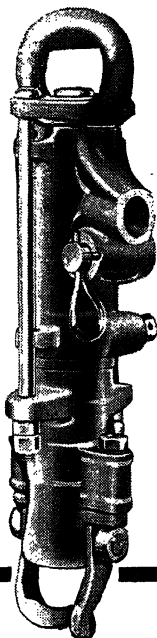
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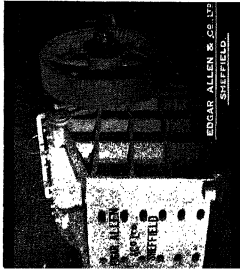
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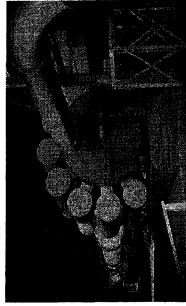
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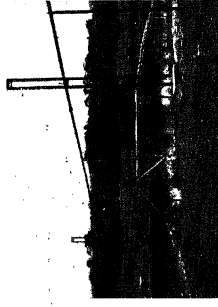
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